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Negative-acknowledgment (NACK)-Oriented
Reliable Multicast (NORM) Protocol

Status of this Memo

This memo defines an Experimental Protocol for the Internet community. It does not specify an Internet standard of any kind. Discussion and suggestions for improvement are requested. Distribution of this memo is unlimited.

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Abstract

This document describes the messages and procedures of the Negative-acknowledgment (NACK) Oriented Reliable Multicast (NORM) protocol. This protocol is designed to provide end-to-end reliable transport of bulk data objects or streams over generic IP multicast routing and forwarding services. NORM uses a selective, negative acknowledgment mechanism for transport reliability and offers additional protocol mechanisms to allow for operation with minimal "a priori" coordination among senders and receivers. A congestion control scheme is specified to allow the NORM protocol to fairly share available network bandwidth with other transport protocols such as Transmission Control Protocol (TCP). It is capable of operating with both reciprocal multicast routing among senders and receivers and with asymmetric connectivity (possibly a unicast return path) between the senders and receivers. The protocol offers a number of features to allow different types of applications or possibly other higher level transport protocols to utilize its service in different ways. The protocol leverages the use of FEC-based repair and other IETF reliable multicast transport (RMT) building blocks in its design.

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1. Introduction and Applicability

The Negative-acknowledgment (NACK) Oriented Reliable Multicast (NORM) protocol is designed to provide reliable transport of data from one or more sender(s) to a group of receivers over an IP multicast network. The primary design goals of NORM are to provide efficient, scalable, and robust bulk data (e.g., computer files, transmission of persistent data) transfer across possibly heterogeneous IP networks and topologies. The NORM protocol design provides support for distributed multicast session participation with minimal coordination among senders and receivers. NORM allows senders and receivers to dynamically join and leave multicast sessions at will with minimal overhead for control information and timing synchronization among participants. To accommodate this capability, NORM protocol message headers contain some common information allowing receivers to easily synchronize to senders throughout the lifetime of a reliable multicast session. NORM is designed to be self-adapting to a wide range of dynamic network conditions with little or no pre-configuration. The protocol is purposely designed to be tolerant of inaccurate timing estimations or lossy conditions that may occur in many networks including mobile and wireless. The protocol is also designed to exhibit convergence and efficient operation even in situations of heavy packet loss and large queuing or transmission delays.

This document is a product of the IETF RMT WG and follows the guidelines provided in RFC 3269 [1]. The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14, RFC 2119 [2].

Statement of Intent

This memo contains part of the definitions necessary to fully specify a Reliable Multicast Transport protocol in accordance with RFC 2357. As per RFC 2357, the use of any reliable multicast protocol in the Internet requires an adequate congestion control scheme.

While waiting for such a scheme to be available, or for an existing scheme to be proven adequate, the Reliable Multicast Transport working group (RMT) publishes this Request for Comments in the "Experimental" category.

It is the intent of RMT to re-submit this specification as an IETF Proposed Standard as soon as the above condition is met.

1.1. NORM Delivery Service Model

A NORM protocol instance (NormSession) is defined within the context of participants communicating connectionless (e.g., Internet Protocol (IP) or User Datagram Protocol (UDP)) packets over a network using pre-determined addresses and host port numbers. Generally, the participants exchange packets using an IP multicast group address, but unicast transport may also be established or applied as an adjunct to multicast delivery. In the case of multicast, the participating NormNodes will communicate using a common IP multicast group address and port number that has been chosen via means outside the context of the given NormSession. Other IETF data format and protocol standards exist that may be applied to describe and convey the required "a priori" information for a specific NormSession (e.g., Session Description Protocol (SDP) [7], Session Announcement Protocol (SAP) [8], etc.).

The NORM protocol design is principally driven by the assumption of a single sender transmitting bulk data content to a group of receivers. However, the protocol MAY operate with multiple senders within the context of a single NormSession. In initial implementations of this protocol, it is anticipated that multiple senders will transmit independent of one another and receivers will maintain state as necessary for each sender. However, in future versions of NORM, it is possible that some aspects of protocol operation (e.g., round-trip time collection) may provide for alternate modes allowing more efficient performance for applications requiring multiple senders.

NORM provides for three types of bulk data content objects (NormObjects) to be reliably transported. These types include:

- 1) static computer memory data content (NORM_OBJECT_DATA type),
- 2) computer storage files (NORM_OBJECT_FILE type), and
- 3) non-finite streams of continuous data content (NORM_OBJECT_STREAM type).

The distinction between NORM_OBJECT_DATA and NORM_OBJECT_FILE is simply to provide a "hint" to receivers in NormSessions serving multiple types of content as to what type of storage should be allocated for received content (i.e., memory or file storage). Other than that distinction, the two are identical, providing for reliable transport of finite (but potentially very large) units of content. These static data and file services are anticipated to be useful for multicast-based cache applications with the ability to reliably provide transmission of large quantities of static data. Other types of static data/file delivery services might make use of these

transport object types, too. The use of the NORM_OBJECT_STREAM type is at the application's discretion and could be used to carry static data or file content also. The NORM reliable stream service opens up additional possibilities such as serialized reliable messaging or other unbounded, perhaps dynamically produced content. The NORM_OBJECT_STREAM provides for reliable transport analogous to that of the Transmission Control Protocol (TCP), although NORM receivers will be able to begin receiving stream content at any point in time. The applicability of this feature will depend upon the application.

The NORM protocol also allows for a small amount of "out-of-band" data (sent as NORM_INFO messages) to be attached to the data content objects transmitted by the sender. This readily-available "out-of-band" data allows multicast receivers to quickly and efficiently determine the nature of the corresponding data, file, or stream bulk content being transmitted. This allows application-level control of the receiver node's participation in the current transport activity. This also allows the protocol to be flexible with minimal pre-coordination among senders and receivers. The NORM_INFO content is designed to be atomic in that its size MUST fit into the payload portion of a single NORM message.

NORM does not provide for global or application-level identification of data content within in its message headers. Note the NORM_INFO out-of-band data mechanism could be leveraged by the application for this purpose if desired, or identification could alternatively be embedded within the data content. NORM does identify transmitted content (NormObjects) with transport identifiers that are applicable only while the sender is transmitting and/or repairing the given object. These transport data content identifiers (NormTransportIds) are assigned in a monotonically increasing fashion by each NORM sender during the course of a NormSession. Each sender maintains its NormTransportId assignments independently so that individual NormObjects may be uniquely identified during transport with the concatenation of the sender session-unique identifier (NormNodeId) and the assigned NormTransportId. The NormTransportIds are assigned from a large, but fixed, numeric space in increasing order and may be reassigned during long-lived sessions. The NORM protocol provides mechanisms so that the sender application may terminate transmission of data content and inform the group of this in an efficient manner. Other similar protocol control mechanisms (e.g., session termination, receiver synchronization, etc.) are specified so that reliable multicast application variants may construct different, complete bulk transfer communication models to meet their goals.

To summarize, the NORM protocol provides reliable transport of different types of data content (including potentially mixed types). The senders enqueue and transmit bulk content in the form of static data or files and/or non-finite, ongoing stream types. NORM senders provide for repair transmission of data and/or FEC content in response to NACK messages received from the receiver group. Mechanisms for "out-of-band" information and other transport control mechanisms are specified for use by applications to form complete reliable multicast solutions for different purposes.

1.2. NORM Scalability

Group communication scalability requirements lead to adaptation of negative acknowledgment (NACK) based protocol schemes when feedback for reliability is required [9]. NORM is a protocol centered around the use of selective NACKs to request repairs of missing data. NORM provides for the use of packet-level forward error correction (FEC) techniques for efficient multicast repair and optional proactive transmission robustness [10]. FEC-based repair can be used to greatly reduce the quantity of reliable multicast repair requests and repair transmissions [11] in a NACK-oriented protocol. The principal factor in NORM scalability is the volume of feedback traffic generated by the receiver set to facilitate reliability and congestion control. NORM uses probabilistic suppression of redundant feedback based on exponentially distributed random backoff timers. The performance of this type of suppression relative to other techniques is described in [12]. NORM dynamically measures the group's roundtrip timing status to set its suppression and other protocol timers. This allows NORM to scale well while maintaining reliable data delivery transport with low latency relative to the network topology over which it is operating.

Feedback messages can be either multicast to the group at large or sent via unicast routing to the sender. In the case of unicast feedback, the sender "advertises" the feedback state to the group to facilitate feedback suppression. In typical Internet environments, it is expected that the NORM protocol will readily scale to group sizes on the order of tens of thousands of receivers. A study of the quantity of feedback for this type of protocol is described in [13]. NORM is able to operate with a smaller amount of feedback than a single TCP connection, even with relatively large numbers of receivers. Thus, depending upon the network topology, it is possible that NORM may scale to larger group sizes. With respect to computer resource usage, the NORM protocol does not require that state be kept on all receivers in the group. NORM senders maintain state only for receivers providing explicit congestion control feedback. NORM receivers must maintain state for each active sender. This may constrain the number of simultaneous senders in some uses of NORM.

1.3. Environmental Requirements and Considerations

All of the environmental requirements and considerations that apply to the RMT NORM Building Block [4] and the RMT FEC Building Block [5] also apply to the NORM protocol.

The NORM protocol SHALL be capable of operating in an end-to-end fashion with no assistance from intermediate systems beyond basic IP multicast group management, routing, and forwarding services. While the techniques utilized in NORM are principally applicable to "flat" end-to-end IP multicast topologies, they could also be applied in the sub-levels of hierarchical (e.g., tree-based) multicast distribution if so desired. NORM can make use of reciprocal (among senders and receivers) multicast communication under the Any-Source Multicast (ASM) model defined in RFC 1112 [3], but SHALL also be capable of scalable operation in asymmetric topologies such as Source Specific Multicast (SSM) [14] where there may only be unicast routing service from the receivers to the sender(s).

NORM is compatible with IPv4 and IPv6. Additionally, NORM may be used with networks employing Network Address Translation (NAT) providing the NAT device supports IP multicast and/or can cache UDP traffic source port numbers for remapping feedback traffic from receivers to the sender(s).

2. Architecture Definition

A NormSession is comprised of participants (NormNodes) acting as senders and/or receivers. NORM senders transmit data content in the form of NormObjects to the session destination address and the NORM receivers attempt to reliably receive the transmitted content using negative acknowledgments to request repair. Each NormNode within a NormSession is assumed to have a preselected unique 32-bit identifier (NormNodeId). NormNodes MUST have uniquely assigned identifiers within a single NormSession to distinguish between possible multiple senders and to distinguish feedback information from different receivers. There are two reserved NormNodeId values. A value of 0x00000000 is considered an invalid NormNodeId value and a value of 0xffffffff is a "wildcard" NormNodeId. While the protocol does not preclude multiple sender nodes concurrently transmitting within the context of a single NORM session (i.e., many-to-many operation), any type of interactive coordination among NORM senders is assumed to be controlled by the application or higher protocol layer. There are some optional mechanisms specified in this document that can be leveraged for such application layer coordination.

As previously noted, NORM allows for reliable transmission of three different basic types of data content. The first type is `NORM_OBJECT_DATA`, which is used for static, persistent blocks of data content maintained in the sender's application memory storage. The second type is `NORM_OBJECT_FILE`, which corresponds to data stored in the sender's non-volatile file system. The `NORM_OBJECT_DATA` and `NORM_OBJECT_FILE` types both represent "NormObjects" of finite but potentially very large size. The third type of data content is `NORM_OBJECT_STREAM`, which corresponds to an ongoing transmission of undefined length. This is analogous to the reliable stream service provided by TCP for unicast data transport. The format of the stream content is application-defined and may be byte or message oriented. The NORM protocol provides for "flushing" of the stream to expedite delivery or possibly enforce application message boundaries. NORM protocol implementations may offer either (or both) in-order delivery of the stream data to the receive application or out-of-order (more immediate) delivery of received segments of the stream to the receiver application. In either case, NORM sender and receiver implementations provide buffering to facilitate repair of the stream as it is transported.

All NormObjects are logically segmented into FEC coding blocks and symbols for transmission by the sender. In NORM, an FEC encoding symbol directly corresponds to the payload of `NORM_DATA` messages or "segment". Note that when systematic FEC codes are used, the payload of `NORM_DATA` messages sent for the first portion of a FEC encoding block are source symbols (actual segments of original user data), while the remaining symbols for the block consist of parity symbols generated by FEC encoding. These parity symbols are generally sent in response to repair requests, but some number may be sent proactively at the end of each encoding block to increase the robustness of transmission. When non-systematic FEC codes are used, all symbols sent consist of FEC encoding parity content. In this case, the receiver must receive a sufficient number of symbols to reconstruct (via FEC decoding) the original user data for the given block. In this document, the terms "symbol" and "segment" are used interchangeably.

Transmitted NormObjects are temporarily yet uniquely identified within the NormSession context using the given sender's `NormNodeId`, `NormInstanceId`, and a temporary `NormObjectTransportId`. Depending upon the implementation, individual NORM senders may manage their `NormInstanceIds` independently, or a common `NormInstanceId` may be agreed upon for all participating nodes within a session if needed as a session identifier. NORM `NormObjectTransportId` data content identifiers are sender-assigned and applicable and valid only during a NormObject's actual `_transport_` (i.e., for as long as the sender is transmitting and providing repair of the indicated NormObject). For

a long-lived session, the NormObjectTransportId field can wrap and previously-used identifiers may be re-used. Note that globally unique identification of transported data content is not provided by NORM and, if required, must be managed by the NORM application. The individual segments or symbols of the NormObject are further identified with FEC payload identifiers which include coding block and symbol identifiers. These are discussed in detail later in this document.

2.1. Protocol Operation Overview

A NORM sender primarily generates messages of type NORM_DATA. These messages carry original data segments or FEC symbols and repair segments/symbols for the bulk data/file or stream NormObjects being transferred. By default, redundant FEC symbols are sent only in response to receiver repair requests (NACKs) and thus normally little or no additional transmission overhead is imposed due to FEC encoding. However, the NORM implementation MAY be optionally configured to proactively transmit some amount of redundant FEC symbols along with the original content to potentially enhance performance (e.g., improved delay) at the cost of additional transmission overhead. This option may be sensible for certain network conditions and can allow for robust, asymmetric multicast (e.g., unidirectional routing, satellite, cable) [15] with reduced receiver feedback, or, in some cases, no feedback.

A sender message of type NORM_INFO is also defined and is used to carry OPTIONAL "out-of-band" context information for a given transport object. A single NORM_INFO message can be associated with a NormObject. Because of its atomic nature, missing NORM_INFO messages can be NACKed and repaired with a slightly lower delay process than NORM's general FEC-encoded data content. NORM_INFO may serve special purposes for some bulk transfer, reliable multicast applications where receivers join the group mid-stream and need to ascertain contextual information on the current content being transmitted. The NACK process for NORM_INFO will be described later. When the NORM_INFO message type is used, its transmission should precede transmission of any NORM_DATA message for the associated NormObject.

The sender also generates messages of type NORM_CMD to assist in certain protocol operations such as congestion control, end-of-transmission flushing, round trip time estimation, receiver synchronization, and optional positive acknowledgment requests or application defined commands. The transmission of NORM_CMD messages from the sender is accomplished by one of three different procedures. These procedures are: single, best effort unreliable transmission of the command; repeated redundant transmissions of the command; and

positively-acknowledged commands. The transmission technique used for a given command depends upon the function of the command. Several core commands are defined for basic protocol operation. Additionally, implementations MAY wish to consider providing the OPTIONAL application-defined commands that can take advantage of the transmission methodologies available for commands. This allows for application-level session management mechanisms that can make use of information available to the underlying NORM protocol engine (e.g., round-trip timing, transmission rate, etc.).

NORM receivers generate messages of type NORM_NACK or NORM_ACK in response to transmissions of data and commands from a sender. The NORM_NACK messages are generated to request repair of detected data transmission losses. Receivers generally detect losses by tracking the sequence of transmission from a sender. Sequencing information is embedded in the transmitted data packets and end-of-transmission commands from the sender. NORM_ACK messages are generated in response to certain commands transmitted by the sender. In the general (and most scalable) protocol mode, NORM_ACK messages are sent only in response to congestion control commands from the sender. The feedback volume of these congestion control NORM_ACK messages is controlled using the same timer-based probabilistic suppression techniques as for NORM_NACK messages to avoid feedback implosion. In order to meet potential application requirements for positive acknowledgment from receivers, other NORM_ACK messages are defined and available for use. All sender and receiver transmissions are subject to rate control governed by a peak transmission rate set for each participant by the application. This can be used to limit the quantity of multicast data transmitted by the group. When NORM's congestion control algorithm is enabled the rate for senders is automatically adjusted. In some networks, it may be desirable to establish minimum and maximum bounds for the rate adjustment depending upon the application even when dynamic congestion control is enabled. However, in the case of the general Internet, congestion control policy SHALL be observed that is compatible with coexistent TCP flows.

2.2. Protocol Building Blocks

The operation of the NORM protocol is based primarily upon the concepts presented in the Nack-Oriented Reliable Multicast (NORM) Building Block document [4]. This includes the basic NORM architecture and the data transmission, repair, and feedback strategies discussed in that document. Additional reliable multicast building blocks are applied in creating the full NORM protocol instantiation [16]. NORM also makes use of Forward Error Correction encoding techniques for repair messaging and optional transmission robustness as described in [10]. NORM uses the FEC Payload ID as

specified by the FEC Building Block Document [5]. Additionally, for congestion control, this document includes a baseline congestion control mechanism (NORM-CC) based on the TCP-Friendly Multicast Congestion Control (TFMCC) scheme described in [19].

2.3. Design Tradeoffs

While the various features of NORM are designed to provide some measure of general purpose utility, it is important to emphasize the understanding that "no one size fits all" in the reliable multicast transport arena. There are numerous engineering tradeoffs involved in reliable multicast transport design and this requires an increased awareness of application and network architecture considerations. Performance requirements affecting design can include: group size, heterogeneity (e.g., capacity and/or delay), asymmetric delivery, data ordering, delivery delay, group dynamics, mobility, congestion control, and transport across low capacity connections. NORM contains various parameters to accommodate many of these differing requirements. The NORM protocol and its mechanisms MAY be applied in multicast applications outside of bulk data transfer, but there is an assumed model of bulk transfer transport service that drives the trade-offs that determine the scalability and performance described in this document.

The ability of NORM to provide reliable data delivery is also governed by any buffer constraints of the sender and receiver applications. NORM protocol implementations SHOULD be designed to operate with the greatest efficiency and robustness possible within application-defined buffer constraints. Buffer requirements for reliability, as always, are a function of the delay-bandwidth product of the network topology. NORM performs best when allowed more buffering resources than typical point-to-point transport protocols. This is because NORM feedback suppression is based upon randomly-delayed transmissions from the receiver set, rather than immediately transmitted feedback. There are definitive tradeoffs between buffer utilization, group size scalability, and efficiency of performance. Large buffer sizes allow the NORM protocol to perform most efficiently in large delay-bandwidth topologies and allow for longer feedback suppression backoff timeouts. This yields improved group size scalability. NORM can operate with reduced buffering but at a cost of decreased efficiency (lower relative goodput) and reduced group size scalability.

3. Conformance Statement

This Protocol Instantiation document, in conjunction with the RMT Building Block documents of [4] and [5], completely specifies a working reliable multicast transport protocol that conforms to the requirements described in RFC 2357 [17].

This document specifies the following message types and mechanisms which are REQUIRED in complying NORM protocol implementations:

Message Type	Purpose
NORM_DATA	Sender message for application data transmission. Implementations must support at least one of the NORM_OBJECT_DATA, NORM_OBJECT_FILE, or NORM_OBJECT_STREAM delivery services. The use of the NORM FEC Object Transmission Information header extension is OPTIONAL with NORM_DATA messages.
NORM_CMD(FLUSH)	Sender command to excite receivers for repair requests in lieu of ongoing NORM_DATA transmissions. Note the use of the NORM_CMD(FLUSH) for positive acknowledgment of data receipt is OPTIONAL.
NORM_CMD(SQUELCH)	Sender command to advertise its current valid repair window in response to invalid requests for repair.
NORM_CMD(REPAIR_ADV)	Sender command to advertise current repair (and congestion control state) to group when unicast feedback messages are detected. Used to control/suppress excessive receiver feedback in asymmetric multicast topologies.
NORM_CMD(CC)	Sender command used in collection of round trip timing and congestion control status from group (this may be OPTIONAL if alternative congestion control mechanism and round trip timing collection is used).
NORM_NACK	Receiver message used to request repair of missing transmitted content.

NORM_ACK	Receiver message used to proactively provide feedback for congestion control purposes. Also used with the OPTIONAL NORM Positive Acknowledgment Process.
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This document also describes the following message types and associated mechanisms which are OPTIONAL for complying NORM protocol implementations:

Message Type	Purpose
NORM_INFO	Sender message for providing ancillary context information associated with NORM transport objects. The use of the NORM FEC Object Transmission Information header extension is OPTIONAL with NORM_INFO messages.
NORM_CMD(EOT)	Sender command to indicate it has reached end-of-transmission and will no longer respond to repair requests.
NORM_CMD(ACK_REQ)	Sender command to support application-defined, positively acknowledged commands sent outside of the context of the bulk data content being transmitted. The NORM Positive Acknowledgment Procedure associated with this message type is OPTIONAL.
NORM_CMD(APPLICATION)	Sender command containing application-defined commands sent outside of the context of the bulk data content being transmitted.
NORM_REPORT	Optional message type reserved for experimental implementations of the NORM protocol.

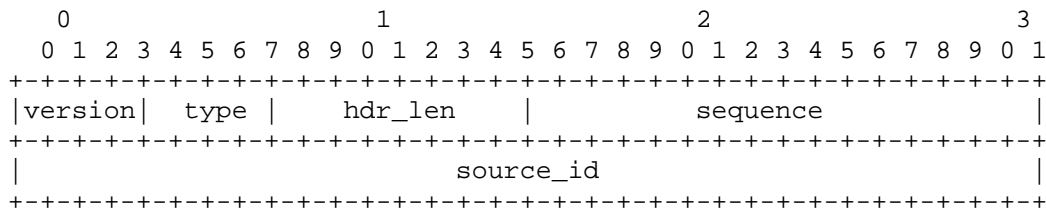
4. Message Formats

As mentioned in Section 2.1, there are two primary classes of NORM messages: sender messages and receiver messages. NORM_CMD, NORM_INFO, and NORM_DATA message types are generated by senders of data content, and NORM_NACK and NORM_ACK messages generated by receivers within a NormSession. An auxiliary message type of

NORM_REPORT is also provided for experimental purposes. This section describes the message formats used by the NORM protocol. These messages and their fields are referenced in the detailed functional description of the NORM protocol given in Section 5. Individual NORM messages are designed to be compatible with the MTU limitations of encapsulating Internet protocols including IPv4, IPv6, and UDP. The current NORM protocol specification assumes UDP encapsulation and leverages the transport features of UDP. The NORM messages are independent of network addresses and can be used in IPv4 and IPv6 networks.

4.1. NORM Common Message Header and Extensions

There are some common message fields contained in all NORM message types. Additionally, a header extension mechanism is defined to expand the functionality of the NORM protocol without revision to this document. All NORM protocol messages begin with a common header with information fields as follows:



NORM Common Message Header Format

The "version" field is a 4-bit value indicating the protocol version number. NORM implementations SHOULD ignore received messages with version numbers different from their own. This number is intended to indicate and distinguish upgrades of the protocol which may be non-interoperable. The NORM version number for this specification is 1.

The message "type" field is a 4-bit value indicating the NORM protocol message type. These types are defined as follows:

Message	Value
NORM_INFO	1
NORM_DATA	2
NORM_CMD	3
NORM_NACK	4
NORM_ACK	5
NORM_REPORT	6

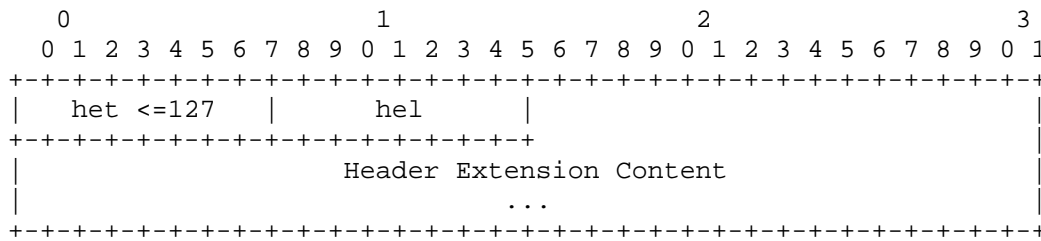
The 8-bit "hdr_len" field indicates the number of 32-bit words that comprise the given message's header portion. This is used to facilitate header extensions that may be applied. The presence of header extensions are implied when the "hdr_len" value is greater than the base value for the given message "type".

The "sequence" field is a 16-bit value that is set by the message originator as a monotonically increasing number incremented with each NORM message transmitted to a given destination address. A "sequence" field number space SHOULD be maintained for messages sent to the NormSession group address. This value can be monitored by receiving nodes to detect packet losses in the transmission from a sender and used in estimating raw packet loss for congestion control purposes. Note that this value is NOT used in the NORM protocol to detect missing reliable data content and does NOT identify the application data or FEC payload that may be attached. With message authentication, the "sequence" field may also be leveraged for protection from message "replay" attacks, particularly of NORM_NACK or other feedback messages. In this case, the receiver node should maintain a monotonically increasing "sequence" field space for each destination to which it transmits (this may be multiple destinations when unicast feedback is used). The size of this field is intended to be sufficient to allow detection of a reasonable range of packet loss within the delay-bandwidth product of expected network connections.

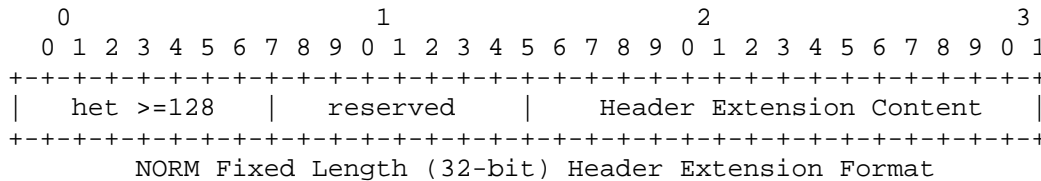
The "source_id" field is a 32-bit value identifying the node that sent the message. A participant's NORM node identifier (NormNodeId) can be set according to application needs but unique identifiers must be assigned within a single NormSession. In some cases, use of the host IP address or a hash of it can suffice, but alternative methodologies for assignment and potential collision resolution of node identifiers within a multicast session need to be considered. For example, the "source identifier" mechanism defined in the Real-Time Protocol (RTP) specification [18] may be applicable to use for NORM node identifiers. At this point in time, the protocol makes no assumptions about how these unique identifiers are actually assigned.

NORM Header Extensions

When header extensions are applied, they follow the message type's base header and precede any payload portion. There are two formats for header extensions, both of which begin with an 8-bit "het" (header extension type) field. One format is provided for variable-length extensions with "het" values in the range from 0 through 127. The other format is for fixed length (one 32-bit word) extensions with "het" values in the range from 128 through 255. These formats are given here:



NORM Variable Length Header Extension Format



The "Header Extension Content" portion of these header extension format is defined for each header extension type defined for NORM messages. Some header extensions are defined within this document for NORM baseline FEC and congestion control operations.

4.2. Sender Messages

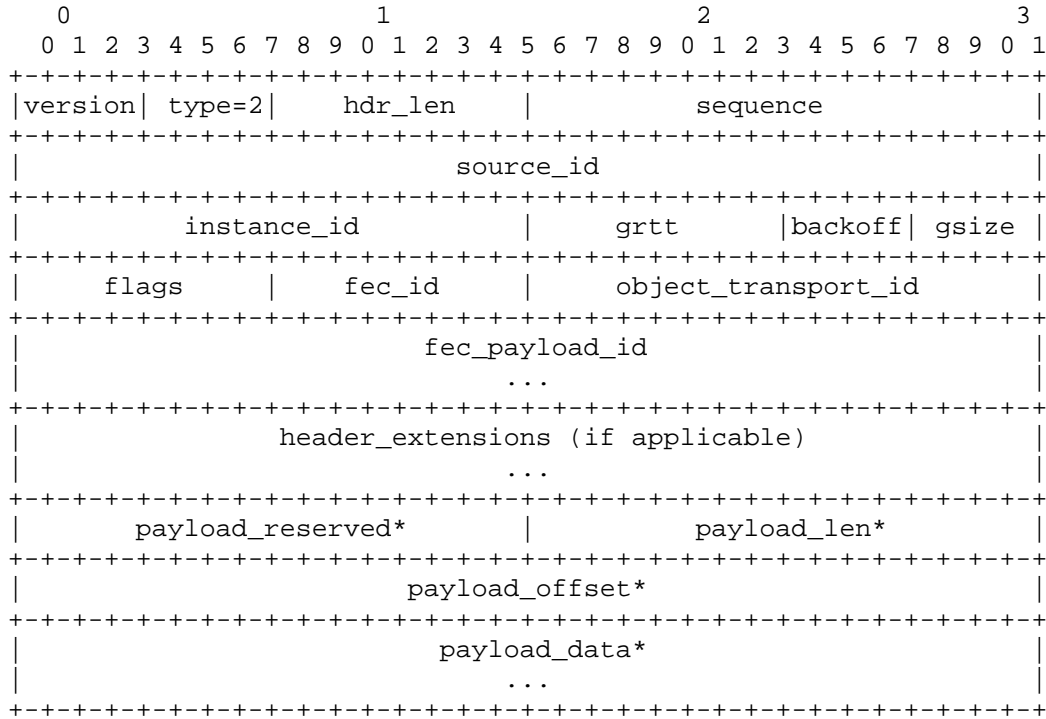
NORM sender messages include the NORM_DATA type, the NORM_INFO type, and the NORM_CMD type. NORM_DATA and NORM_INFO messages contain application data content while NORM_CMD messages are used for various protocol control functions.

4.2.1. NORM_DATA Message

The NORM_DATA message is expected to be the predominant type transmitted by NORM senders. These messages are used to encapsulate segmented data content for objects of type NORM_OBJECT_DATA, NORM_OBJECT_FILE, and NORM_OBJECT_STREAM. NORM_DATA messages may contain original or FEC-encoded application data content.

The format of NORM_DATA messages is comprised of three logical portions: 1) a fixed-format NORM_DATA header portion, 2) a FEC Payload ID portion with a format dependent upon the FEC encoding used, and 3) a payload portion containing source or encoded application data content. Note for objects of type NORM_OBJECT_STREAM, the payload portion contains additional fields used to appropriately recover stream content. NORM implementations MAY also extend the NORM_DATA header to include a FEC Object

Transmission Information (EXT_FTI) header extension. This allows NORM receivers to automatically allocate resources and properly perform FEC decoding without the need for pre-configuration or out-of-band information.



NORM_DATA Message Format

*NOTE: The "payload_reserved", "payload_len" and "payload_offset" fields are present only for objects of type NORM_OBJECT_STREAM. The "payload_len" and "payload_offset" fields allow senders to arbitrarily vary the size of NORM_DATA payload segments for streams. This allows applications to flush transmitted streams as needed to meet unique streaming requirements. For objects of types NORM_OBJECT_FILE and NORM_OBJECT_DATA, these fields are unnecessary since the receiver can calculate the payload length and offset information from the "fec_payload_id" using the algorithm described in Section 5.1.1. The "payload_reserved" field is kept for anticipated future NORM stream control functions. When systematic FEC codes (e.g., "fec_id" = 129) are used, the "payload_len" and "payload_offset" fields contain actual length and offset values for the encapsulated application data segment for those NORM_DATA messages containing source data symbols. In NORM_DATA messages that contain parity information, these fields are not actual length or

offset values, but instead are values computed from FEC encoding the "payload_len" and "payload_offset" fields of the _source_data symbols of the corresponding applicable coding block.

The "version", "type", "hdr_len", "sequence", and "source_id" fields form the NORM Common Message Header as described in Section 4.1. The value of the NORM_DATA "type" field is 2. The NORM_DATA _base_ "hdr_len" value is 4 (32-bit words) plus the size of the "fec_payload_id" field. The "fec_payload_id" field size depends upon the FEC encoding used for the referenced NormObject. The "fec_id" field is used to indicate the FEC coding type. For example, when small block, systematic codes are used, a "fec_id" value of 129 is indicated and the size of the "fec_payload_id" is two 32-bit words. In this case the NORM_DATA base "hdr_len" value is 6. The cumulative size of any header extensions applied is added into the "hdr_len" field.

The "instance_id" field contains a value generated by the sender to uniquely identify its current instance of participation in the NormSession. This allows receivers to detect when senders have perhaps left and rejoined a session in progress. When a sender (identified by its "source_id") is detected to have a new "instance_id", the NORM receivers SHOULD drop their previous state on the sender and begin reception anew.

The "grtt" field contains a non-linear quantized representation of the sender's current estimate of group round-trip time (GRTT) (this is also referred to as R_max in [19]). This value is used to control timing of the NACK repair process and other aspects of protocol operation as described in this document. The algorithm for encoding and decoding this field is described in the RMT NORM Building Block document [4].

The "backoff" field value is used by receivers to determine the maximum backoff timer value used in the timer-based NORM NACK feedback suppression. This 4-bit field supports values from 0-15 which is multiplied by the sender GRTT to determine the maximum backoff timeout. The "backoff" field informs the receiver set of the sender's backoff factor parameter "Ksender". Recommended values and their use are described in the NORM receiver NACK procedure description in Section 5.3. The "gsize" field contains a representation of the sender's current estimate of group size. This 4-bit field can roughly represent values from ten to 500 million where the most significant bit value of 0 or 1 represents a mantissa of 1 or 5, respectively and the three least significant bits incremented by one represent a base 10 exponent (order of magnitude). For examples, a field value of "0x0" represents 1.0e+01 (10), a value of "0x8" represents 5.0e+01 (50), a value of "0x1" represents 1.0e+02

(100), and a value of "0xf" represents 5.0e+08. For NORM feedback suppression purposes, the group size does not need to be represented with a high degree of precision. The group size may even be estimated somewhat conservatively (i.e., overestimated) to maintain low levels of feedback traffic. A default group size estimate of 10,000 ("gsize" = 0x4) is recommended for general purpose reliable multicast applications using the NORM protocol.

The "flags" field contains a number of different binary flags providing information and hints regarding how the receiver should handle the identified object. Defined flags in this field include:

Flag	Value	Purpose
NORM_FLAG_REPAIR	0x01	Indicates message is a repair transmission
NORM_FLAG_EXPLICIT	0x02	Indicates a repair segment intended to meet a specific receiver erasure, as compared to parity segments provided by the sender for general purpose (with respect to an FEC coding block) erasure filling.
NORM_FLAG_INFO	0x04	Indicates availability of NORM_INFO for object.
NORM_FLAG_UNRELIABLE	0x08	Indicates that repair transmissions for the specified object will be unavailable (One-shot, best effort transmission).
NORM_FLAG_FILE	0x10	Indicates object is "file-based" data (hint to use disk storage for reception).
NORM_FLAG_STREAM	0x20	Indicates object is of type NORM_OBJECT_STREAM.
NORM_FLAG_MSG_START	0x40	Marks the first segment of application messages embedded in NORM_OBJECT_STREAMs.

NORM_FLAG_REPAIR is set when the associated message is a repair transmission. This information can be used by receivers to help observe a join policy where it is desired that newly joining receivers only begin participating in the NACK process upon receipt

of new (non-repair) data content. NORM_FLAG_EXPLICIT is used to mark repair messages sent when the data sender has exhausted its ability to provide "fresh" (previously untransmitted) parity segments as repair. This flag could possibly be used by intermediate systems implementing functionality to control sub-casting of repair content to different legs of a reliable multicast topology with disparate repair needs. NORM_FLAG_INFO is set only when optional NORM_INFO content is actually available for the associated object. Thus, receivers will NACK for retransmission of NORM_INFO only when it is available for a given object. NORM_FLAG_UNRELIABLE is set when the sender wishes to transmit an object with only "best effort" delivery and will not supply repair transmissions for the object. NORM receivers SHOULD NOT execute repair requests for objects marked with the NORM_FLAG_UNRELIABLE flag. Note that receivers may inadvertently request repair of such objects when all segments (or info content) for those objects are not received (i.e., a gap in the "object_transport_id" sequence is noted). In this case, the sender should invoke the NORM_CMD(SQUELCH) process as described in Section 4.2.3. NORM_FLAG_FILE can be set as a "hint" from the sender that the associated object should be stored in non-volatile storage. NORM_FLAG_STREAM is set when the identified object is of type NORM_OBJECT_STREAM. When NORM_FLAG_STREAM is set, the NORM_FLAG_MSG_START can be optionally used to mark the first data segments of application-layer messages transported within the NORM stream. This allows NORM receiver applications to "synchronize" with NORM senders and to be able to properly interpret application layer data when joining a NORM session already in progress. In practice, the NORM implementation MAY set this flag for the segment transmitted following an explicit "flush" of the stream by the application.

The "fec_id" field corresponds to the FEC Encoding Identifier described in the FEC Building Block document [5]. The "fec_id" value implies the format of the "fec_payload_id" field and, coupled with FEC Object Transmission Information, the procedures to decode FEC encoded content. Small block, systematic codes ("fec_id" = 129) are expected to be used for most NORM purposes and the NORM_OBJECT_STREAM requires systematic FEC codes for most efficient performance.

The "object_transport_id" field is a monotonically and incrementally increasing value assigned by the sender to NormObjects being transmitted. Transmissions and repair requests related to that object use the same "object_transport_id" value. For sessions of very long or indefinite duration, the "object_transport_id" field may be repeated, but it is presumed that the 16-bit field size provides an adequate enough sequence space to avoid object confusion amongst receivers and sources (i.e., receivers SHOULD re-synchronize with a server when receiving object sequence identifiers sufficiently out-of-range with the current state kept for a given source). During the

course of its transmission within a NORM session, an object is uniquely identified by the concatenation of the sender "source_id" and the given "object_transport_id". Note that NORM_INFO messages associated with the identified object carry the same "object_transport_id" value.

The "fec_payload_id" identifies the attached NORM_DATA "payload" content. The size and format of the "fec_payload_id" field depends upon the FEC type indicated by the "fec_id" field. These formats are given in the FEC Building Block document [5] and any subsequent extensions of that document. As an example, the format of the "fec_payload_id" format small block, systematic codes ("fec_id" = 129) given here:

0										1										2										3																			
0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9										
+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+																																																	
										source_block_number																																							
+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+																																																	
										source_block_len																				encoding_symbol_id																			
+-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+																																																	

Small Block, Systematic Code ("fec_id" = 129) "fec_payload_id" Format

The FEC payload identifier "source_block_number", "source_block_len", and "encoding_symbol_id" fields correspond to the "Source Block Number", "Source Block Length, and "Encoding Symbol ID" fields of the FEC Payload ID format given by the IETF FEC Building Block document [5]. The "source_block_number" identifies the coding block's relative position with a NormObject. Note that, for NormObjects of type NORM_OBJECT_STREAM, the "source_block_number" may wrap for very long lived sessions. The "source_block_len" indicates the number of user data segments in the identified coding block. Given the "source_block_len" information of how many symbols of application data are contained in the block, the receiver can determine whether the attached segment is data or parity content and treat it appropriately. The "encoding_symbol_id" identifies which specific symbol (segment) within the coding block the attached payload conveys. Depending upon the value of the "encoding_symbol_id" and the associated "source_block_len" parameters for the block, the symbol (segment) referenced may be a user data or an FEC parity segment. For systematic codes, encoding symbols numbered less than the source_block_len contain original application data while segments greater than or equal to source_block_len contain parity symbols calculated for the block. The concatenation of

`object_transport_id::fec_payload_id` can be viewed as a unique transport protocol data unit identifier for the attached segment with respect to the NORM sender's instance within a session.

Additional FEC Object Transmission Information (as described in the FEC Building Block document [5]) is required to properly receive and decode NORM transport objects. This information MAY be provided as out-of-band session information. However, in some cases, it may be useful for the sender to include this information "in band" to facilitate receiver operation with minimal preconfiguration. For this purpose, the NORM FEC Object Transmission Information Header Extension (EXT_FTI) is defined. This header extension MAY be applied to NORM_DATA and NORM_INFO messages to provide this necessary information. The exact format of the extension depends upon the FEC code in use, but in general it SHOULD contain any required details on the FEC code in use (e.g., FEC Instance ID, etc.) and the byte size of the associated NormObject (For the NORM_OBJECT_STREAM type, this size corresponds to the stream buffer size maintained by the NORM sender). As an example, the format of the EXT_FTI for small block systematic codes ("fec_id" = 129) is given here:

0										1										2										3									
0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1								
het = 64										hel = 4										object_length (msb)																			
object_length (lsb)																																							
fec_instance_id										segment_size																													
fec_max_block_len										fec_num_parity																													

FEC Object Transmission Information Header Extension (EXT_FTI) for Small Block Systematic Codes ("fec id" = 129)

The header extension type "het" field value for this header extension is 64. The header extension length "hel" depends upon the format of the FTI for FEC code type identified by the "fec_id" field. In this example (for "fec id" = 129), the "hel" field value is 4.

The 48-bit "object_length" field indicates the total size of the object (in bytes) for the static object types of NORM_OBJECT_FILE and NORM_OBJECT_DATA. This information is used by receivers to determine storage requirements and/or allocate storage for the received object. Receivers with insufficient storage capability may wish to forego reliable reception (i.e., not NACK for) of the indicated object. In the case of objects of type NORM OBJECT STREAM, the "object length"

field is used by the sender to indicate the size of its stream buffer to the receiver group. In turn, the receivers SHOULD use this information to allocate a stream buffer for reception of corresponding size.

The "fec_instance_id" corresponds to the "FEC Instance ID" described in the FEC Building Block document [5]. In this case, the "fec_instance_id" SHALL be a value corresponding to the particular type of Small Block Systematic Code being used (e.g., Reed-Solomon GF(2⁸), Reed-Solomon GF(2¹⁶), etc). The standardized assignment of FEC Instance ID values is described in [5]. The "segment_size" field indicates the sender's current setting for maximum message payload content (in bytes). This allows receivers to allocate appropriate buffering resources and to determine other information in order to properly process received data messaging.

The "fec_max_block_len" indicates the current maximum number of user data segments per FEC coding block to be used by the sender during the session. This allows receivers to allocate appropriate buffer space for buffering blocks transmitted by the sender.

The "fec_num_parity" corresponds to the "maximum number of encoding symbols that can be generated for any source block" as described in for FEC Object Transmission Information for Small Block Systematic Codes in the FEC Building Block document [5]. For example, Reed-Solomon codes may be arbitrarily shortened to create different code variations for a given block length. In the case of Reed-Solomon (GF(2⁸) and GF(2¹⁶)) codes, this value indicates the maximum number of parity segments available from the sender for the coding blocks. This field MAY be interpreted differently for other systematic codes as they are defined.

The payload portion of NORM_DATA messages includes source data or FEC encoded application content.

The "payload_reserved", "payload_len" and "payload_offset" fields are present ONLY for transport objects of type NORM_OBJECT_STREAM. These fields indicate the size and relative position (within the stream) of the application content represented by the message payload. For senders employing systematic FEC encoding, these fields contain _actual_ length and offset values (in bytes) for the payload of messages which contain original data source symbols. For NORM_DATA messages containing calculated parity content, these fields will actually contain values computed by FEC encoding of the "payload_len" and "payload_offset" values of the NORM_DATA data segments of the corresponding FEC coding block. Thus, the "payload_len" and "payload_offset" values of missing data content can be determined upon decoding a FEC coding block. Note that these fields do NOT

contribute to the value of the NORM_DATA "hdr_len" field. These fields are NOT present when the "flags" portion of the NORM_DATA message indicate the transport object is of type NORM_OBJECT_FILE or NORM_OBJECT_DATA. In this case, the length and offset information can be calculated from the "fec_payload_id" using the methodology described in Section 5.1.1. Note that for long-lived streams, the "payload_offset" field can wrap.

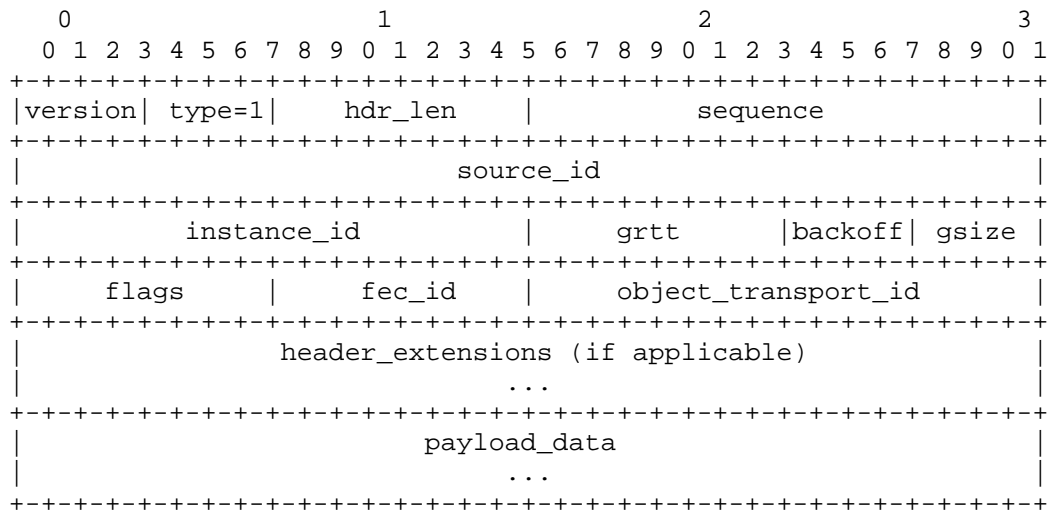
The "payload_data" field contains the original application source or parity content for the symbol identified by the "fec_payload_id". The length of this field SHALL be limited to a maximum of the sender's NormSegmentSize bytes as given in the FTI for the object. Note the length of this field for messages containing parity content will always be of length NormSegmentSize. When encoding data segments of varying sizes, the FEC encoder SHALL assume ZERO value padding for data segments with length less than the NormSegmentSize. It is RECOMMENDED that a sender's NormSegmentSize generally be constant for the duration of a given sender's term of participation in the session, but may possibly vary on a per-object basis. The NormSegmentSize is expected to be configurable by the sender application prior to session participation as needed for network topology maximum transmission unit (MTU) considerations. For IPv6, MTU discovery may be possibly leveraged at session startup to perform this configuration. The "payload_data" content may be delivered directly to the application for source symbols (when systematic FEC encoding is used) or upon decoding of the FEC block. For NORM_OBJECT_FILE and NORM_OBJECT_STREAM objects, the data segment length and offset can be calculated using the algorithm described in Section 5.1.1. For NORM_OBJECT_STREAM objects, the length and offset is obtained from the segment's corresponding "payload_len" and "payload_offset" fields.

4.2.2. NORM_INFO Message

The NORM_INFO message is used to convey OPTIONAL, application-defined, "out-of-band" context information for transmitted NormObjects. An example NORM_INFO use for bulk file transfer is to place MIME type information for the associated file, data, or stream object into the NORM_INFO payload. Receivers may use the NORM_INFO content to make a decision as whether to participate in reliable reception of the associated object. Each NormObject can have an independent unit of NORM_INFO associated with it. NORM_DATA messages contain a flag to indicate the availability of NORM_INFO for a given NormObject. NORM receivers may NACK for retransmission of NORM_INFO when they have not received it for a given NormObject. The size of the NORM_INFO content is limited to that of a single NormSegmentSize

for the given sender. This atomic nature allows the NORM_INFO to be rapidly and efficiently repaired within the NORM reliable transmission process.

When NORM_INFO content is available for a NormObject, the NORM_FLAG_INFO flag SHALL be set in NORM_DATA messages for the corresponding "object_transport_id" and the NORM_INFO message shall be transmitted as the first message for the NormObject.



NORM_INFO Message Format

The "version", "type", "hdr_len", "sequence", and "source_id" fields form the NORM Common Message Header as described in Section 4.1. The value of "hdr_len" field when no header extensions are present is 4.

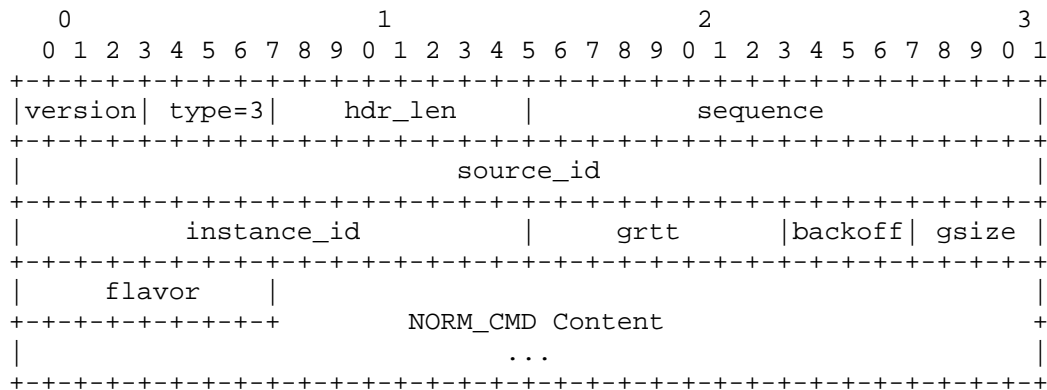
The "instance_id", "grtt", "backoff", "gsize", "flags", "fec_id", and "object_transport_id" fields carry the same information and serve the same purpose as with NORM_DATA messages. These values allow the receiver to prepare appropriate buffering, etc, for further transmissions from the sender when NORM_INFO is the first message received.

As with NORM_DATA messages, the NORM FTI Header Extension (EXT_FTI) may be optionally applied to NORM_INFO messages. To conserve protocol overhead, some NORM implementations may wish to apply the EXT_FTI when used to NORM_INFO messages only and not to NORM_DATA messages.

The NORM_INFO "payload_data" field contains sender application-defined content which can be used by receiver applications for various purposes as described above.

4.2.3. NORM_CMD Messages

NORM_CMD messages are transmitted by senders to perform a number of different protocol functions. This includes functions such as round-trip timing collection, congestion control functions, synchronization of sender/receiver repair "windows", and notification of sender status. A core set of NORM_CMD messages is enumerated. Additionally, a range of command types remain available for potential application-specific use. Some NORM_CMD types may have dynamic content attached. Any attached content will be limited to maximum length of the sender NormSegmentSize to retain the atomic nature of commands. All NORM_CMD messages begin with a common set of fields, after the usual NORM message common header. The standard NORM_CMD fields are:



NORM_CMD Standard Fields

The "version", "type", "hdr_len", "sequence", and "source_id" fields form the NORM Common Message Header as described in Section 4.1. The value of the "hdr_len" field for NORM_CMD messages without header extensions present depends upon the "flavor" field.

The "instance_id", "grtt", "backoff", and "gsize" fields provide the same information and serve the same purpose as with NORM_DATA and NORM_INFO messages. The "flavor" field indicates the type of command to follow. The remainder of the NORM_CMD message is dependent upon the command type ("flavor"). NORM command flavors include:

Command	Flavor Value	Purpose
NORM_CMD(FLUSH)	1	Used to indicate sender temporary end-of-transmission. (Assists in robustly initiating outstanding repair requests from receivers). May also be optionally used to collect positive acknowledgment of reliable reception from subset of receivers.
NORM_CMD(EOT)	2	Used to indicate sender permanent end-of-transmission.
NORM_CMD(SQUELCH)	3	Used to advertise sender's current repair window in response to out-of-range NACKs from receivers.
NORM_CMD(CC)	4	Used for GRTT measurement and collection of congestion control feedback.
NORM_CMD(REPAIR_ADV)	5	Used to advertise sender's aggregated repair/feedback state for suppression of unicast feedback from receivers.
NORM_CMD(ACK_REQ)	6	Used to request application-defined positive acknowledgment from a list of receivers (OPTIONAL).
NORM_CMD(APPLICATION)	7	Used for application-defined purposes which may need to temporarily preempt data transmission (OPTIONAL).

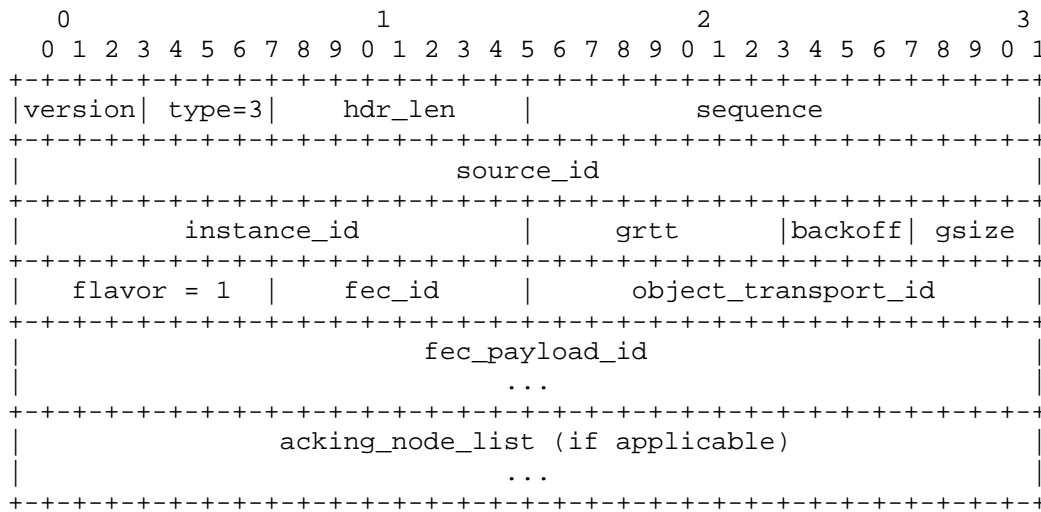
4.2.3.1. NORM_CMD(FLUSH) Message

The NORM_CMD(FLUSH) command is sent when the sender reaches the end of all data content and pending repairs it has queued for transmission. This may indicate a temporary or permanent end of data transmission, but the sender is still willing to respond to repair requests. This command is repeated once per 2*GRTT to excite the

receiver set for any outstanding repair requests up to and including the transmission point indicated within the NORM_CMD(FLUSH) message. The number of repeats is equal to NORM_ROBUST_FACTOR unless a list of receivers from which explicit positive acknowledgment is expected ("acking_node_list") is given. In that case, the "acking_node_list" is updated as acknowledgments are received and the NORM_CMD(FLUSH) is repeated according to the mechanism described in Section 5.5.3. The greater the NORM_ROBUST_FACTOR, the greater the probability that all applicable receivers will be excited for acknowledgment or repair requests (NACKs) _and_ that the corresponding NACKs are delivered to the sender. If a NORM_NACK message interrupts the flush process, the sender will re-initiate the flush process after any resulting repair transmissions are completed.

Note that receivers also employ a timeout mechanism to self-initiate NACKing (if there are outstanding repair needs) when no messages of any type are received from a sender. This inactivity timeout is related to $2 * GRTT * NORM_ROBUST_FACTOR$ and will be discussed more later. With a sufficient NORM_ROBUST_FACTOR value, data content is delivered with a high assurance of reliability. The penalty of a large NORM_ROBUST_FACTOR value is potentially excess sender NORM_CMD(FLUSH) transmissions and a longer timeout for receivers to self-initiate the terminal NACK process.

For finite-size transport objects such as NORM_OBJECT_DATA and NORM_OBJECT_FILE, the flush process (if there are no further pending objects) occurs at the end of these objects. Thus, FEC repair information is always available for repairs in response to repair requests elicited by the flush command. However, for NORM_OBJECT_STREAM, the flush may occur at any time, including in the middle of an FEC coding block if systematic FEC codes are employed. In this case, the sender will not yet be able to provide FEC parity content as repair for the concurrent coding block and will be limited to explicitly repairing stream data content for that block. Applications that anticipate frequent flushing of stream content SHOULD be judicious in the selection of the FEC coding block size (i.e., do not use a very large coding block size if frequent flushing occurs). For example, a reliable multicast application transmitting an on-going series of intermittent, relatively small messaging content will need to trade-off using the NORM_OBJECT_DATA paradigm versus the NORM_OBJECT_STREAM paradigm with an appropriate FEC coding block size. This is analogous to application trade-offs for other transport protocols such as the selection of different TCP modes of operation such as "no delay", etc.



NORM_CMD(FLUSH) Message Format

In addition to the NORM common message header and standard NORM_CMD fields, the NORM_CMD(FLUSH) message contains fields to identify the current status and logical transmit position of the sender.

The "fec_id" field indicates the FEC type used for the flushing "object_transport_id" and implies the size and format of the "fec_payload_id" field. Note the "hdr_len" value for the NORM_CMD(FLUSH) message is 4 plus the size of the "fec_payload_id" field when no header extensions are present.

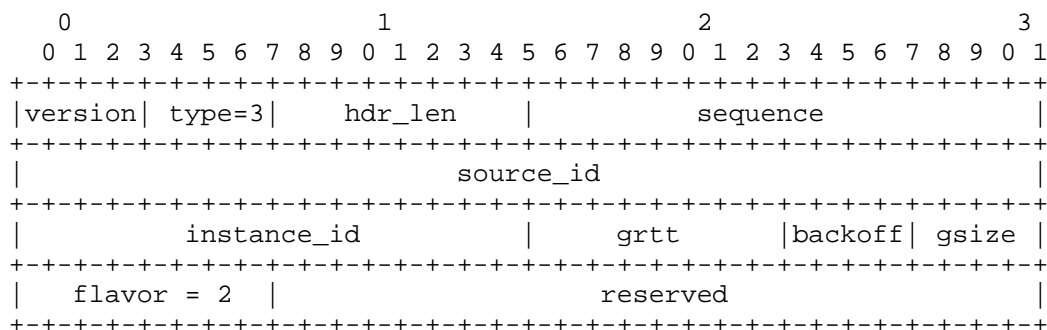
The "object_transport_id" and "fec_payload_id" fields indicate the sender's current logical "transmit position". These fields are interpreted in the same manner as in the NORM_DATA message type. Upon receipt of the NORM_CMD(FLUSH), receivers are expected to check their completion state `_through_` (including) this transmission position. If receivers have outstanding repair needs in this range, they SHALL initiate the NORM NACK Repair Process as described in Section 5.3. If receivers have no outstanding repair needs, no response to the NORM_CMD(FLUSH) is generated.

For NORM_OBJECT_STREAM objects using systematic FEC codes, receivers MUST request "explicit-only" repair of the identified "source_block_number" if the given "encoding_symbol_id" is less than the "source_block_len". This condition indicates the sender has not yet completed encoding the corresponding FEC block and parity content is not yet available. An "explicit-only" repair request consists of NACK content for the applicable "source_block_number" which does not include any requests for parity-based repair. This allows NORM

sender applications to "flush" an ongoing stream of transmission when needed, even if in the middle of an FEC block. Once the sender resumes stream transmission and passes the end of the pending coding block, subsequent NACKs from receivers SHALL request parity-based repair as usual. Note that the use of a systematic FEC code is assumed here. Normal receiver NACK initiation and construction is discussed in detail in Section 5.3. The OPTIONAL "acking_node_list" field contains a list of NormNodeIds for receivers from which the sender is requesting explicit positive acknowledgment of reception up through the transmission point identified by the "object_transport_id" and "fec_payload_id" fields. The length of the list can be inferred from the length of the received NORM_CMD(FLUSH) message. When the "acking_node_list" is present, the lightweight positive acknowledgment process described in Section 5.5.3 SHALL be observed.

4.2.3.2. NORM_CMD(EOT) Message

The NORM_CMD(EOT) command is sent when the sender reaches permanent end-of-transmission with respect to the NormSession and will not respond to further repair requests. This allows receivers to gracefully reach closure of operation with this sender (without requiring any timeout) and free any resources that are no longer needed. The NORM_CMD(EOT) command SHOULD be sent with the same robust mechanism as used for NORM_CMD(FLUSH) commands to provide a high assurance of reception by the receiver set.



NORM_CMD(EOT) Message Format

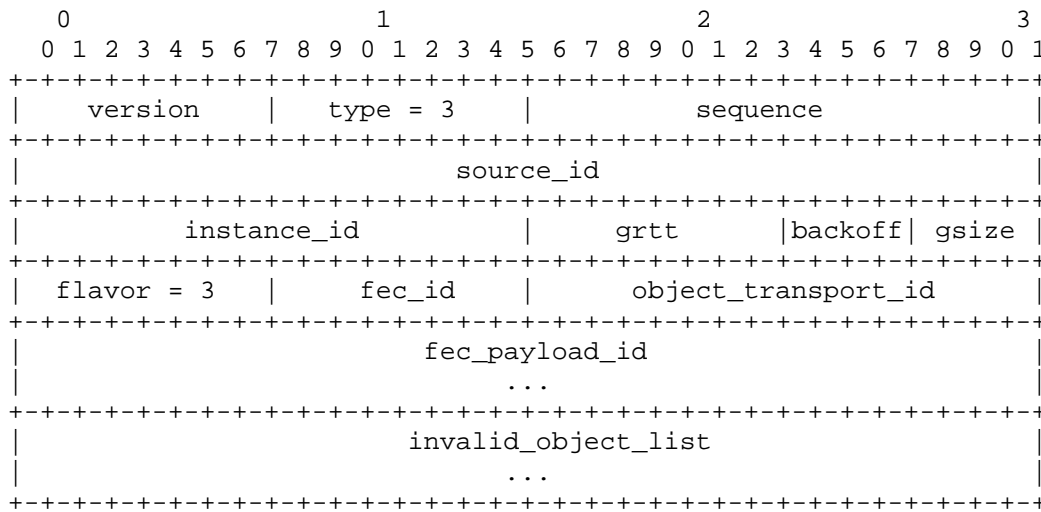
The value of the "hdr_len" field for NORM_CMD(EOT) messages without header extensions present is 4. The "reserved" field is reserved for future use and MUST be set to an all ZERO value. Receivers MUST ignore the "reserved" field.

4.2.3.3. NORM_CMD(SQUELCH) Message

The NORM_CMD(SQUELCH) command is transmitted in response to outdated or invalid NORM_NACK content received by the sender. Invalid NORM_NACK content consists of repair requests for NormObjects for which the sender is unable or unwilling to provide repair. This includes repair requests for outdated objects, aborted objects, or those objects which the sender previously transmitted marked with the NORM_FLAG_UNRELIABLE flag. This command indicates to receivers what content is available for repair, thus serving as a description of the sender's current "repair window". Receivers SHALL not generate repair requests for content identified as invalid by a NORM_CMD(SQUELCH).

The NORM_CMD(SQUELCH) command is sent once per 2*GRTT at the most. The NORM_CMD(SQUELCH) advertises the current "repair window" of the sender by identifying the earliest (lowest) transmission point for which it will provide repair, along with an encoded list of objects from that point forward that are no longer valid for repair. This mechanism allows the sender application to cancel or abort transmission and/or repair of specific previously enqueued objects. The list also contains the identifiers for any objects within the repair window that were sent with the NORM_FLAG_UNRELIABLE flag set. In normal conditions, it is expected the NORM_CMD(SQUELCH) will be needed infrequently, and generally only to provide a reference repair window for receivers who have fallen "out-of-sync" with the sender due to extremely poor network conditions.

The starting point of the invalid NormObject list begins with the lowest invalid NormTransportId greater than the current "repair window" start from the invalid NACK(s) that prompted the generation of the squelch. The length of the list is limited by the sender's NormSegmentSize. This allows the receivers to learn the status of the sender's applicable object repair window with minimal transmission of NORM_CMD(SQUELCH) commands. The format of the NORM_CMD(SQUELCH) message is:



NORM_CMD(SQUELCH) Message Format

In addition to the NORM common message header and standard NORM_CMD fields, the NORM_CMD(SQUELCH) message contains fields to identify the earliest logical transmit position of the sender's current repair window and an "invalid object list" beginning with the index of the logically earliest invalid repair request from the offending NACK message which initiated the squelch transmission.

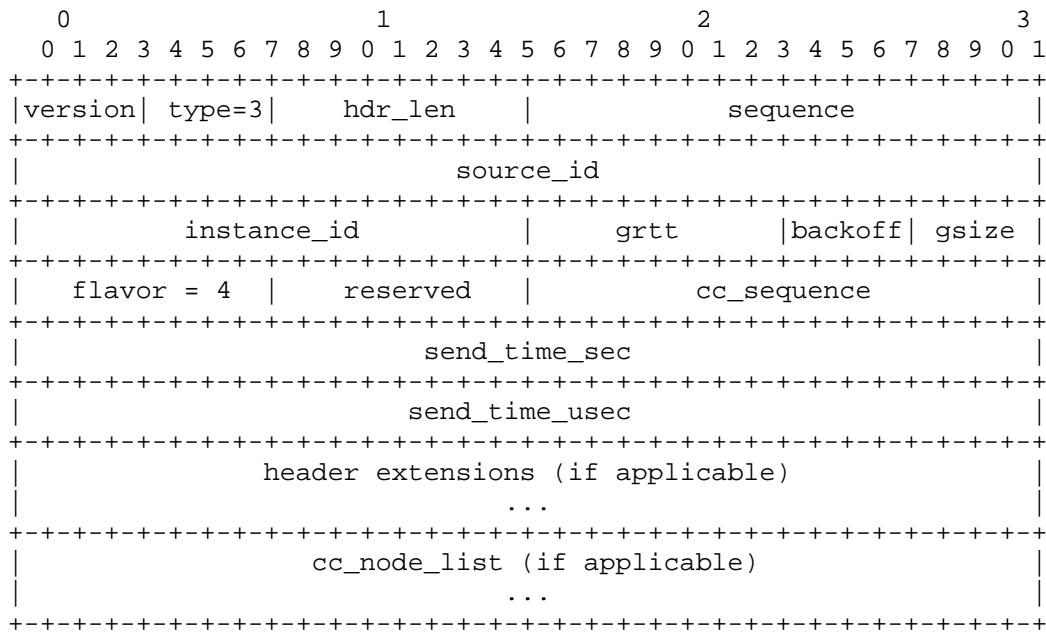
The "object_transport_id" and "fec_payload_id" fields are concatenated to indicate the beginning of the sender's current repair window (i.e., the logically earliest point in its transmission history for which the sender can provide repair). The "fec_id" field implies the size and format of the "fec_payload_id" field. This serves as an advertisement of a "synchronization point" for receivers to request repair. Note, that while an "encoding_symbol_id" may be included in the "fec_payload_id" field, the sender's repair window SHOULD be aligned on FEC coding block boundaries and thus the "encoding_symbol_id" SHOULD be zero.

The "invalid_object_list" is a list of 16-bit NormTransportIds that, although they are within the range of the sender's current repair window, are no longer available for repair from the sender. For example, a sender application may dequeue an out-of-date object even though it is still within the repair window. The total size of the "invalid_object_list" content is can be determined from the packet's payload length and is limited to a maximum of the NormSegmentSize of the sender. Thus, for very large repair windows, it is possible that a single NORM_CMD(SQUELCH) message may not be capable of listing the entire set of invalid objects in the repair window. In this case,

the sender SHALL ensure that the list begins with a NormObjectId that is greater than or equal to the lowest ordinal invalid NormObjectId from the NACK message(s) that prompted the NORM_CMD(SQUELCH) generation. The NormObjectIds in the "invalid_object_list" MUST be greater than the "object_transport_id" marking the beginning of the sender's repair window. This insures convergence of the squelch process, even if multiple invalid NACK/ squelch iterations are required. This explicit description of invalid content within the sender's current window allows the sender application (most notably for discrete "object" based transport) to arbitrarily invalidate (i.e., dequeue) portions of enqueued content (e.g., certain objects) for which it no longer wishes to provide reliable transport.

4.2.3.4. NORM_CMD(CC) Message

The NORM_CMD(CC) messages contains fields to enable sender-to-receiver group greatest round-trip time (GRTT) measurement and to excite the group for congestion control feedback. A baseline NORM congestion control scheme (NORM-CC), based on the TCP-Friendly Multicast Congestion Control (TFMCC) scheme of [19] is described in Section 5.5.2 of this document. The NORM_CMD(CC) message is usually transmitted as part of NORM-CC congestion control operation. A NORM header extension is defined below to be used with the NORM_CMD(CC) message to support NORM-CC operation. Different header extensions may be defined for the NORM_CMD(CC) (and/or other NORM messages as needed) to support alternative congestion control schemes in the future. If NORM is operated in a private network with congestion control operation disabled, the NORM_CMD(CC) message is then used for GRTT measurement only and may optionally be sent less frequently than with congestion control operation.



NORM_CMD(CC) Message Format

The NORM common message header and standard NORM_CMD fields serve their usual purposes.

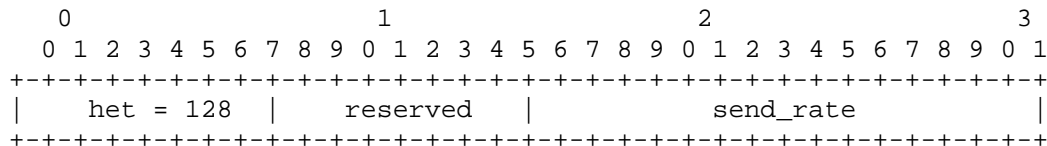
The "reserved" field is for potential future use and should be set to ZERO in this version of the NORM protocol.

The "cc_sequence" field is a sequence number applied by the sender. For NORM-CC operation, it is used to provide functionality equivalent to the "feedback round number" (fb_nr) described in [19]. The most recently received "cc_sequence" value is recorded by receivers and can be fed back to the sender in congestion control feedback generated by the receivers for that sender. The "cc_sequence" number can also be used in NORM implementations to assess how recently a receiver has received NORM_CMD(CC) probes from the sender. This can be useful instrumentation for complex or experimental multicast routing environments.

The "send_time" field is a timestamp indicating the time that the NORM_CMD(CC) message was transmitted. This consists of a 64-bit field containing 32-bits with the time in seconds ("send_time_sec") and 32-bits with the time in microseconds ("send_time_usec") since some reference time the source maintains (usually 00:00:00, 1 January 1970). The byte ordering of the fields is "Big Endian" network order. Receivers use this timestamp adjusted by the amount of delay

from the time they received the NORM_CMD(CC) message to the time of their response as the "grtt_response" portion of NORM_ACK and NORM_NACK messages generated. This allows the sender to evaluate round-trip times to different receivers for congestion control and other (e.g., GRTT determination) purposes.

To facilitate the baseline NORM-CC scheme described in Section 5.5.2, a NORM-CC Rate header extension (EXT_RATE) is defined to inform the group of the sender's current transmission rate. This is used along with the loss detection "sequence" field of all NORM sender messages and the NORM_CMD(CC) GRTT collection process to support NORM-CC congestion control operation. The format of this header extension is as follows:



NORM-CC Rate Header Extension Format (EXT_RATE)

The "send_rate" field indicates the sender's current transmission rate in bytes per second. The 16-bit "send_rate" field consists of 12 bits of mantissa in the most significant portion and 4 bits of base 10 exponent (order of magnitude) information in the least significant portion. The 12-bit mantissa portion of the field is scaled such that a floating point value of 0.0 corresponds to 0 and a floating point value of 10.0 corresponds to 4096. Thus:

```
send_rate = (((int)(Value_mantissa * 4096.0 / 10.0 + 0.5)) << 4) |
Value_exponent;
```

For example, to represent a transmission rate of 256kbps (3.2e+04 bytes per second), the lower 4 bits of the 16-bit field contain a value of 0x04 to represent the exponent while the upper 12 bits contain a value of 0x51f as determined from the equation given above:

```
send_rate = (((int)((3.2 * 4096.0 / 10.0) + 0.5)) << 4) | 4;

           = (0x51f << 4) | 0x4

           = 0x51f4
```

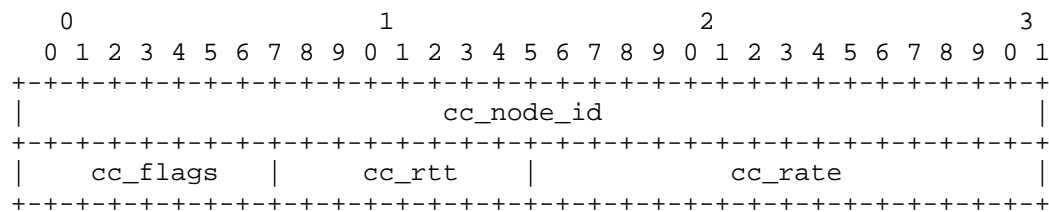
To decode the "send_rate" field, the following equation can be used:

```
value = (send_rate >> 4) * 10.0 / 4096.0 *
        power(10.0, (send_rate & x000f))
```

Note the maximum transmission rate that can be represented by this scheme is approximately 9.99e+15 bytes per second.

When this extension is present, a "cc_node_list" may be attached as the payload of the NORM_CMD(CC) message. The presence of this header extension also implies that NORM receivers should respond according to the procedures described in Section 5.5.2. The "cc_node_list" consists of a list of NormNodeIds and their associated congestion control status. This includes the current limiting receiver (CLR) node, any potential limiting receiver (PLR) nodes that have been identified, and some number of receivers for which congestion control status is being provided, most notably including the receivers' current RTT measurement. The maximum length of the "cc_node_list" provides for at least the CLR and one other receiver, but may be configurable for more timely feedback to the group. The list length can be inferred from the length of the NORM_CMD(CC) message.

Each item in the "cc_node_list" is in the following format:



Congestion Control Node List Item Format

The "cc_node_id" is the NormNodeId of the receiver which the item represents.

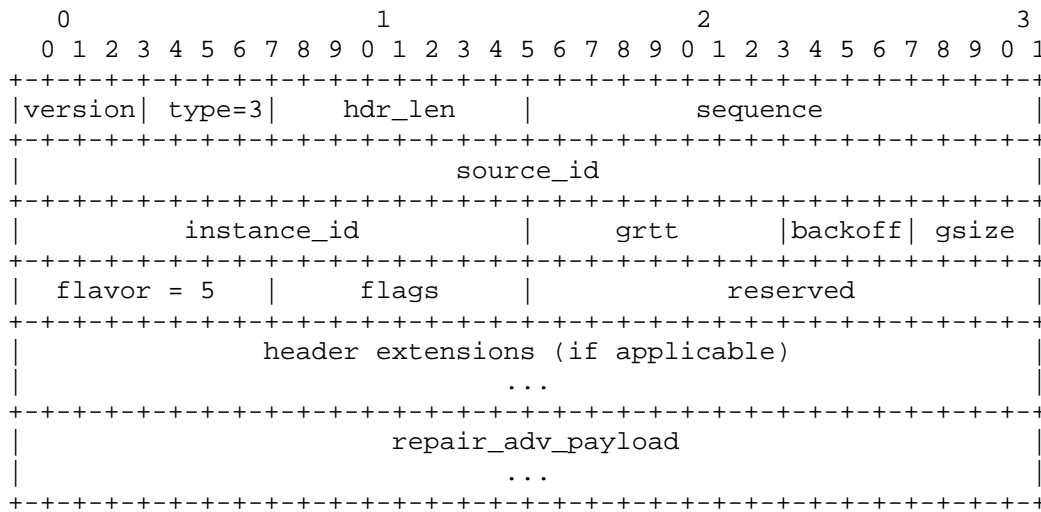
The "cc_flags" field contains flags indicating the congestion control status of the indicated receiver. The following flags are defined:

Flag	Value	Purpose
NORM_FLAG_CC_CLR	0x01	Receiver is the current limiting receiver (CLR).
NORM_FLAG_CC_PLR	0x02	Receiver is a potential limiting receiver (PLR).
NORM_FLAG_CC_RTT	0x04	Receiver has measured RTT with respect to sender.
NORM_FLAG_CC_START	0x08	Sender/receiver is in "slow start" phase of congestion control operation (i.e., The receiver has not yet detected any packet loss and the "cc_rate" field is the receiver's actual measured receive rate).
NORM_FLAG_CC_LEAVE	0x10	Receiver is imminently leaving the session and its feedback should not be considered in congestion control operation.

The "cc_rtt" contains a quantized representation of the RTT as measured by the sender with respect to the indicated receiver. This field is valid only if the NORM_FLAG_CC_RTT flag is set in the "cc_flags" field. This one byte field is a quantized representation of the RTT using the algorithm described in the NORM Building Block document [4]. The "cc_rate" field contains a representation of the receiver's current calculated (during steady-state congestion control operation) or twice its measured (during the "slow start" phase) congestion control rate. This field is encoded and decoded using the same technique as described for the NORM_CMD(CC) "send_rate" field.

4.2.3.5. NORM_CMD(REPAIR_ADV) Message

The NORM_CMD(REPAIR_ADV) message is used by the sender to "advertise" its aggregated repair state from NORM_NACK messages accumulated during a repair cycle and/or congestion control feedback received. This message is sent only when the sender has received NORM_NACK and/or NORM_ACK(CC) (when congestion control is enabled) messages via unicast transmission instead of multicast. By "echoing" this information to the receiver set, suppression of feedback can be achieved even when receivers are unicasting that feedback instead of multicasting it among the group [13].



NORM_CMD(REPAIR_ADV) Message Format

The "instance_id", "grtt", "backoff", "gsize", and "flavor" fields serve the same purpose as in other NORM_CMD messages. The value of the "hdr_len" field when no extensions are present is 4.

The "flags" field provide information on the NORM_CMD(REPAIR_ADV) content. There is currently one NORM_CMD(REPAIR_ADV) flag defined:

NORM_REPAIR_ADV_FLAG_LIMIT = 0x01

This flag is set by the sender when it is unable to fit its full current repair state into a single NormSegmentSize. If this flag is set, receivers should limit their NACK response to generating NACK content only up through the maximum ordinal transmission position (objectId::fecPayloadId) included in the "repair_adv_content".

When congestion control operation is enabled, a header extension may be applied to the NORM_CMD(REPAIR_ADV) representing the most limiting (in terms of congestion control feedback suppression) congestion control response. This allows the NORM_CMD(REPAIR_ADV) message to suppress receiver congestion control responses as well as NACK feedback messages. The field is defined as a header extension so that alternative congestion control schemes may be used with NORM without revision to this document. A NORM-CC Feedback Header Extension (EXT_CC) is defined to encapsulate congestion control feedback within NORM_NACK, NORM_ACK, and NORM_CMD(REPAIR_ADV) messages. If another congestion control technique (e.g., Pragmatic General Multicast Congestion Control (PGMCC) [20]) is used within a

NORM implementation, an additional header extension MAY need to be defined to encapsulate any required feedback content. The NORM-CC Feedback Header Extension format is:

```

+-----+-----+-----+-----+-----+-----+-----+-----+
|   het = 3   |   hel = 3   |             cc_sequence             |
+-----+-----+-----+-----+-----+-----+-----+-----+
|   cc_flags   |   cc_rtt   |             cc_loss             |
+-----+-----+-----+-----+-----+-----+-----+-----+
|             cc_rate             |             cc_reserved             |
+-----+-----+-----+-----+-----+-----+-----+-----+

```

NORM-CC Feedback Header Extension (EXT_CC) Format

The "cc_sequence" field contains the current greatest "cc_sequence" value receivers have received in NORM_CMD(CC) messages from the sender. This information assists the sender in congestion control operation by providing an indicator of how current ("fresh") the receiver's round-trip measurement reference time is and whether the receiver has been successfully receiving recent congestion control probes. For example, if it is apparent the receiver has not been receiving recent congestion control probes (and thus possibly other messages from the sender), the sender may choose to take congestion avoidance measures. For NORM_CMD(REPAIR_ADV) messages, the sender SHALL set the "cc_sequence" field value to the value set in the last NORM_CMD(CC) message sent.

The "cc_flags" field contains bits representing the receiver's state with respect to congestion control operation. The possible values for the "cc_flags" field are those specified for the NORM_CMD(CC) message node list item flags. These fields are used by receivers in controlling (suppressing as necessary) their congestion control feedback. For NORM_CMD(REPAIR_ADV) messages, the NORM_FLAG_CC_RTT should be set only when all feedback messages received by the sender have the flag set. Similarly, the NORM_FLAG_CC_CLR or NORM_FLAG_CC_PLR should be set only when no feedback has been received from non-CLR or non-PLR receivers. And the NORM_FLAG_CC_LEAVE should be set only when all feedback messages the sender has received have this flag set. These heuristics for setting the flags in NORM_CMD(REPAIR_ADV) ensure the most effective suppression of receivers providing unicast feedback messages.

The "cc_rtt" field SHALL be set to a default maximum value and the NORM_FLAG_CC_RTT flag SHALL be cleared when no receiver has yet received RTT measurement information. When a receiver has received RTT measurement information, it shall set the "cc_rtt" value accordingly and set the NORM_FLAG_CC_RTT flag in the "cc_flags" field.

For NORM_CMD(REPAIR_ADV) messages, the sender SHALL set the "cc_rtt" field value to the largest non-CLR/non-PLR RTT it has measured from receivers for the current feedback round.

The "cc_loss" field represents the receiver's current packet loss fraction estimate for the indicated source. The loss fraction is a value from 0.0 to 1.0 corresponding to a range of zero to 100 percent packet loss. The 16-bit "cc_loss" value is calculated by the following formula:

$$\text{"cc_loss"} = \text{decimal_loss_fraction} * 65535.0$$

For NORM_CMD(REPAIR_ADV) messages, the sender SHALL set the "cc_loss" field value to the largest non-CLR/non-PLR loss estimate it has received from receivers for the current feedback round.

The "cc_rate" field represents the receivers current local congestion control rate. During "slow start", when the receiver has detected no loss, this value is set to twice the actual rate it has measured from the corresponding sender and the NORM_FLAG_CC_START is set in the "cc_flags" field. Otherwise, the receiver calculates a congestion control rate based on its loss measurement and RTT measurement information (even if default) for the "cc_rate" field. For NORM_CMD(REPAIR_ADV) messages, the sender SHALL set the "cc_loss" field value to the lowest non-CLR/non-PLR "cc_rate" report it has received from receivers for the current feedback round.

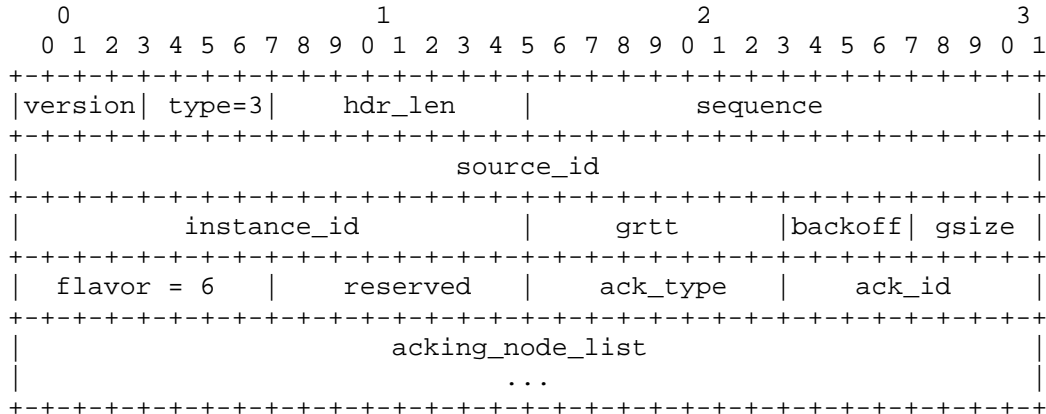
The "cc_reserved" field is reserved for future NORM protocol use. Currently, senders SHALL set this field to ZERO, and receivers SHALL ignore the content of this field.

The "repair_adv_payload" is in exactly the same form as the "nack_content" of NORM_NACK messages and can be processed by receivers for suppression purposes in the same manner, with the exception of the condition when the NORM_REPAIR_ADV_FLAG_LIMIT is set.

4.2.3.6. NORM_CMD(ACK_REQ) Message

The NORM_CMD(ACK_REQ) message is used by the sender to request acknowledgment from a specified list of receivers. This message is used in providing a lightweight positive acknowledgment mechanism that is OPTIONAL for use by the reliable multicast application. A range of acknowledgment request types is provided for use at the application's discretion. Provision for application-defined, positively-acknowledged commands allows the application to automatically take advantage of transmission and round-trip timing information available to the NORM protocol. The details of the NORM

positive acknowledgment process including transmission of the NORM_CMD(ACK_REQ) messages and the receiver response (NORM_ACK) are described in Section 5.5.3. The format of the NORM_CMD(ACK_REQ) message is:



NORM_CMD(ACK_REQ) Message Format

The NORM common message header and standard NORM_CMD fields serve their usual purposes. The value of the "hdr_len" field for NORM_CMD(ACK_REQ) messages with no header extension present is 4.

The "ack_type" field indicates the type of acknowledgment being requested and thus implies rules for how the receiver will treat this request. The following "ack_type" values are defined and are also used in NORM_ACK messages described later:

ACK Type	Value	Purpose
NORM_ACK_CC	1	Used to identify NORM_ACK messages sent in response to NORM_CMD(CC) messages.
NORM_ACK_FLUSH	2	Used to identify NORM_ACK messages sent in response to NORM_CMD(FLUSH) messages.
NORM_ACK_RESERVED	3-15	Reserved for possible future NORM protocol use.
NORM_ACK_APPLICATION	16-255	Used at application's discretion.

The NORM_ACK_CC value is provided for use only in NORM_ACKs generated in response to the NORM_CMD(CC) messages used in congestion control operation. Similarly, the NORM_ACK_FLUSH is provided for use only in NORM_ACKs generated in response to applicable NORM_CMD(FLUSH) messages. NORM_CMD(ACK_REQ) messages with "ack_type" of NORM_ACK_CC or NORM_ACK_FLUSH SHALL NOT be generated by the sender.

The NORM_ACK_RESERVED range of "ack_type" values is provided for possible future NORM protocol use.

The NORM_ACK_APPLICATION range of "ack_type" values is provided so that NORM applications may implement application-defined, positively-acknowledged commands that are able to leverage internal transmission and round-trip timing information available to the NORM protocol implementation.

The "ack_id" provides a sequenced identifier for the given NORM_CMD(ACK_REQ) message. This "ack_id" is returned in NORM_ACK messages generated by the receivers so that the sender may associate the response with its corresponding request.

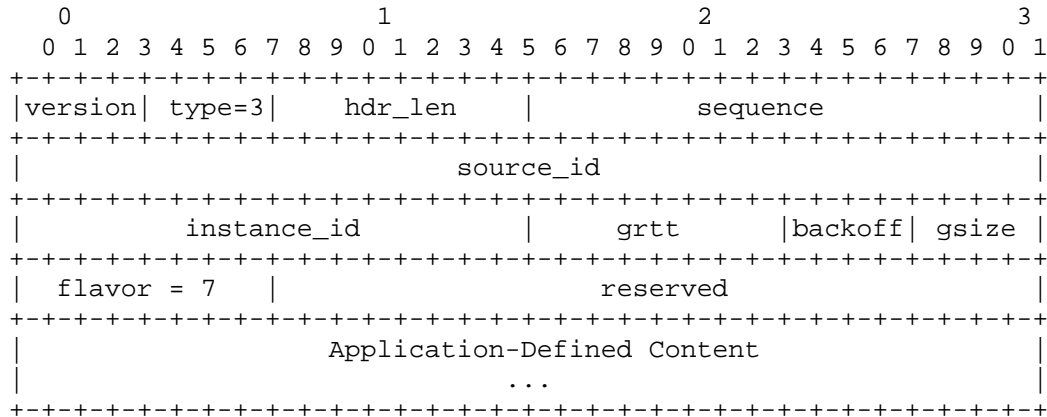
The "reserved" field is reserved for possible future protocol use and SHALL be set to ZERO by senders and ignored by receivers.

The "acking_node_list" field contains the NormNodeIds of the current NORM receivers that are desired to provide positive acknowledge (NORM_ACK) to this request. The packet payload length implies the length of the "acking_node_list" and its length is limited to the sender NormSegmentSize. The individual NormNodeId items are listed in network (Big Endian) byte order. If a receiver's NormNodeId is included in the "acking_node_list", it SHALL schedule transmission of a NORM_ACK message as described in Section 5.5.3.

4.2.3.7. NORM_CMD(APPLICATION) Message

This command allows the NORM application to robustly transmit application-defined commands. The command message preempts any ongoing data transmission and is repeated up to NORM_ROBUST_FACTOR times at a rate of once per 2*GRTT. This rate of repetition allows the application to observe any response (if that is the application's purpose for the command) before it is repeated. Possible responses may include initiation of data transmission, other NORM_CMD(APPLICATION) messages, or even application-defined, positively-acknowledge commands from other NormSession participants. The transmission of these commands will preempt data transmission when they are scheduled and may be multiplexed with ongoing data transmission. This type of robustly transmitted command allows NORM applications to define a complete set of session control mechanisms

with less state than the transfer of FEC encoded reliable content requires while taking advantage of NORM transmission and round-trip timing information.



NORM_CMD(APPLICATION) Message Format

The NORM common message header and NORM_CMD fields are interpreted as previously described. The value of the NORM_CMD(APPLICATION) "hdr_len" field when no header extensions are present is 4.

The "Application-Defined Content" area contains information in a format at the discretion of the application. The size of this payload SHALL be limited to a maximum of the sender's NormSegmentSize setting.

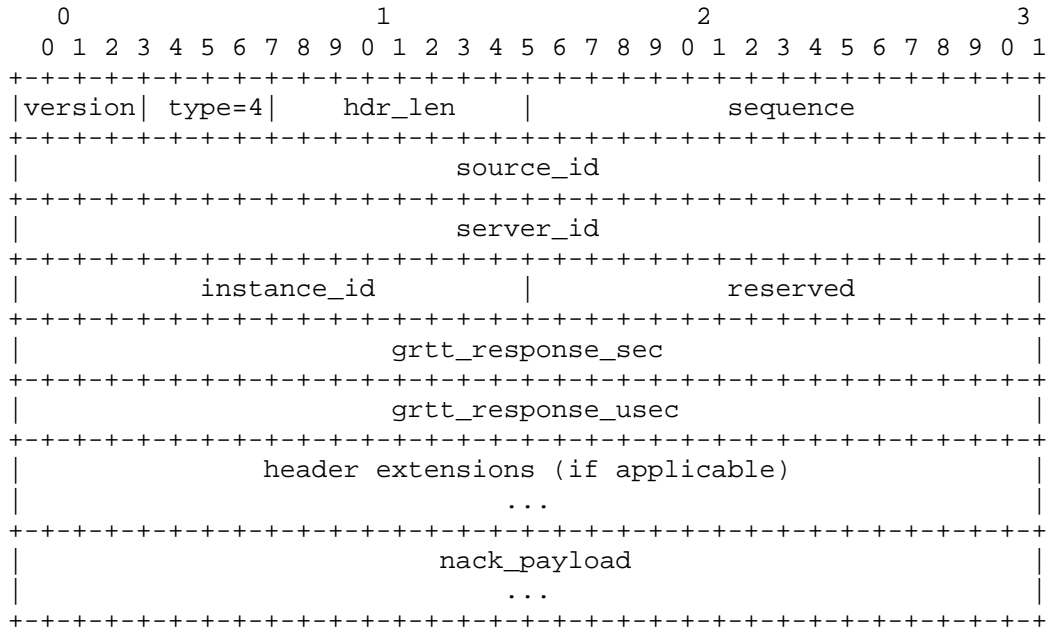
4.3. Receiver Messages

The NORM message types generated by participating receivers consist of NORM_NACK and NORM_ACK message types. NORM_NACK messages are sent to request repair of missing data content from sender transmission and NORM_ACK messages are generated in response to certain sender commands including NORM_CMD(CC) and NORM_CMD(ACK_REQ).

4.3.1. NORM_NACK Message

The principal purpose of NORM_NACK messages is for receivers to request repair of sender content via selective, negative acknowledgment upon detection of incomplete data. NORM_NACK messages will be transmitted according to the rules of NORM_NACK generation and suppression described in Section 5.3. NORM_NACK messages also contain additional fields to provide feedback to the sender(s) for purposes of round-trip timing collection and congestion control.

The payload of NORM_NACK messages contains one or more repair requests for different objects or portions of those objects. The NORM_NACK message format is as follows:



NORM_NACK Message Format

The NORM common message header fields serve their usual purposes. The value of the "hdr_len" field for NORM_NACK messages without header extensions present is 6.

The "server_id" field identifies the NORM sender to which the NORM_NACK message is destined.

The "instance_id" field contains the current session identifier given by the sender identified by the "server_id" field in its sender messages. The sender SHOULD ignore feedback messages which contain an invalid "instance_id" value.

The "grtt_response" fields contain an adjusted version of the timestamp from the most recently received NORM_CMD(CC) message for the indicated NORM sender. The format of the "grtt_response" is the same as the "send_time" field of the NORM_CMD(CC). The "grtt_response" value is relative to the "send_time" the source provided with a corresponding NORM_CMD(CC) command. The receiver adjusts the source's NORM_CMD(CC) "send_time" timestamp by adding the time differential from when the receiver received the NORM_CMD(CC)

to when the NORM_NACK is transmitted to calculate the value in the "grtt_response" field. This is the "receive_to_response_differential" value used in the following formula:

```
"grtt_response" = NORM_CMD(CC) "send_time" +
receive_to_response_differential
```

The receiver SHALL set the "grtt_response" to a ZERO value, to indicate that it has not yet received a NORM_CMD(CC) message from the indicated sender and that the sender should ignore the "grtt_response" in this message.

For NORM-CC operation, the NORM-CC Feedback Header Extension, as described in the NORM_CMD(REPAIR_ADV) message description, is added to NORM_NACK messages to provide feedback on the receivers current state with respect to congestion control operation. Note that alternative header extensions for congestion control feedback may be defined for alternative congestion control schemes for NORM use in the future.

The "reserved" field is for potential future NORM use and SHALL be set to ZERO for this version of the protocol.

The "nack_content" of the NORM_NACK message specifies the repair needs of the receiver with respect to the NORM sender indicated by the "server_id" field. The receiver constructs repair requests based on the NORM_DATA and/or NORM_INFO segments it requires from the sender in order to complete reliable reception up to the sender's transmission position at the moment the receiver initiates the NACK Procedure as described in Section 5.3. A single NORM Repair Request consists of a list of items, ranges, and/or FEC coding block erasure counts for needed NORM_DATA and/or NORM_INFO content. Multiple repair requests may be concatenated within the "nack_payload" field of a NORM_NACK message. Note that a single NORM Repair Request can possibly include multiple "items", "ranges", or "erasure_counts". In turn, the "nack_payload" field may contain multiple repair requests. A single NORM Repair Request has the following format:

```

      0               1               2               3
    0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
|           form           |      flags      |           length      |
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+
|                                     repair_request_items                                     |
|                                     ...                                     |
+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+---+

```

NORM Repair Request Format

The "form" field indicates the type of repair request items given in the "repair_request_items" list. Possible values for the "form" field include:

Form	Value
NORM_NACK_ITEMS	1
NORM_NACK_RANGES	2
NORM_NACK_ERASURES	3

A "form" value of NORM_NACK_ITEMS indicates each repair request item in the "repair_request_items" list is to be treated as an individual request. A value of NORM_NACK_RANGES indicates that the "repair_request_items" list consists of pairs of repair request items that correspond to inclusive ranges of repair needs. And the NORM_NACK_ERASURES "form" indicates that the repair request items are to be treated individually and that the "encoding_symbol_id" portion of the "fec_payload_id" field of the repair request item (see below) is to be interpreted as an "erasure count" for the FEC coding block identified by the repair request item's "source_block_number".

The "flags" field is currently used to indicate the level of data content for which the repair request items apply (i.e., an individual segment, entire FEC coding block, or entire transport object). Possible flag values include:

Flag	Value	Purpose
NORM_NACK_SEGMENT	0x01	Indicates the listed segment(s) or range of segments are required as repair.
NORM_NACK_BLOCK	0x02	Indicates the listed block(s) or range of blocks in entirety are required as repair.
NORM_NACK_INFO	0x04	Indicates that NORM_INFO is required as repair for the listed object(s).
NORM_NACK_OBJECT	0x08	Indicates the listed object(s) or range of objects in entirety are required as repair.

When the NORM_NACK_SEGMENT flag is set, the "object_transport_id" and "fec_payload_id" fields are used to determine which sets or ranges of individual NORM_DATA segments are needed to repair content at the

receiver. When the NORM_NACK_BLOCK flag is set, this indicates the receiver is completely missing the indicated coding block(s) and requires transmissions sufficient to repair the indicated block(s) in their entirety. When the NORM_NACK_INFO flag is set, this indicates the receiver is missing the NORM_INFO segment for the indicated "object_transport_id". Note the NORM_NACK_INFO may be set in combination with the NORM_NACK_BLOCK or NORM_NACK_SEGMENT flags, or may be set alone. When the NORM_NACK_OBJECT flag is set, this indicates the receiver is missing the entire NormTransportObject referenced by the "object_transport_id". This also implicitly requests any available NORM_INFO for the NormObject, if applicable. The "fec_payload_id" field is ignored when the flag NORM_NACK_OBJECT is set.

The "length" field value is the length in bytes of the "repair_request_items" field.

The "repair_request_items" field consists of a list of individual or range pairs of transport data unit identifiers in the following format.

0										1										2										3									
0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
fec_id										reserved										object_transport_id																			
										fec_payload_id																													
										...																													

NORM Repair Request Item Format

The "fec_id" indicates the FEC type and can be used to determine the format of the "fec_payload_id" field. The "reserved" field is kept for possible future use and SHALL be set to a ZERO value and ignored by NORM nodes processing NACK content.

The "object_transport_id" corresponds to the NormObject for which repair is being requested and the "fec_payload_id" identifies the specific FEC coding block and/or segment being requested. When the NORM_NACK_OBJECT flag is set, the value of the "fec_payload_id" field is ignored. When the NORM_NACK_BLOCK flag is set, only the FEC code block identifier portion of the "fec_payload_id" is to be interpreted.

The format of the "fec_payload_id" field depends upon the "fec_id" field value.

When the receiver's repair needs dictate that different forms (mixed ranges and/or individual items) or types (mixed specific segments and/or blocks or objects in entirety) are required to complete reliable transmission, multiple NORM Repair Requests with different "form" and or "flags" values can be concatenated within a single NORM_NACK message. Additionally, NORM receivers SHALL construct NORM_NACK messages with their repair requests in ordinal order with respect to "object_transport_id" and "fec_payload_id" values. The "nack_payload" size SHALL NOT exceed the NormSegmentSize for the sender to which the NORM_NACK is destined.

NORM_NACK Content Examples:

In these examples, a small block, systematic FEC code ("fec_id" = 129) is assumed with a user data block length of 32 segments. In Example 1, a list of individual NORM_NACK_ITEMS repair requests is given. In Example 2, a list of NORM_NACK_RANGES requests _and_ a single NORM_NACK_ITEMS request are concatenated to illustrate the possible content of a NORM_NACK message. Note that FEC coding block erasure counts could also be provided in each case. However, the erasure counts are not really necessary since the sender can easily determine the erasure count while processing the NACK content. However, the erasure count option may be useful for operation with other FEC codes or for intermediate system purposes.

Example 1: NORM_NACK "nack_payload" for: Object 12, Coding Block 3, Segments 2,5,8

```

0          1          2          3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-----+-----+-----+-----+
| form = 1 | flags = 0x01 | length = 36 |
+-----+-----+-----+-----+
| fec_id = 129 | reserved | object_transport_id = 12 |
+-----+-----+-----+-----+
| source_block_number = 3 |
+-----+-----+-----+-----+
| source_block_length = 32 | encoding_symbol_id = 2 |
+-----+-----+-----+-----+
| fec_id = 129 | reserved | object_transport_id = 12 |
+-----+-----+-----+-----+
| source_block_number = 3 |
+-----+-----+-----+-----+
| source_block_length = 32 | encoding_symbol_id = 5 |
+-----+-----+-----+-----+
| fec_id = 129 | reserved | object_transport_id = 12 |
+-----+-----+-----+-----+
| source_block_number = 3 |
+-----+-----+-----+-----+
| source_block_length = 32 | encoding_symbol_id = 8 |
+-----+-----+-----+-----+

```

Example 2: NORM_NACK "nack_payload" for: Object 18 Coding Block 6, Segments 5, 6, 7, 8, 9, 10; and Object 19 NORM_INFO and Coding Block 1, segment 3

```

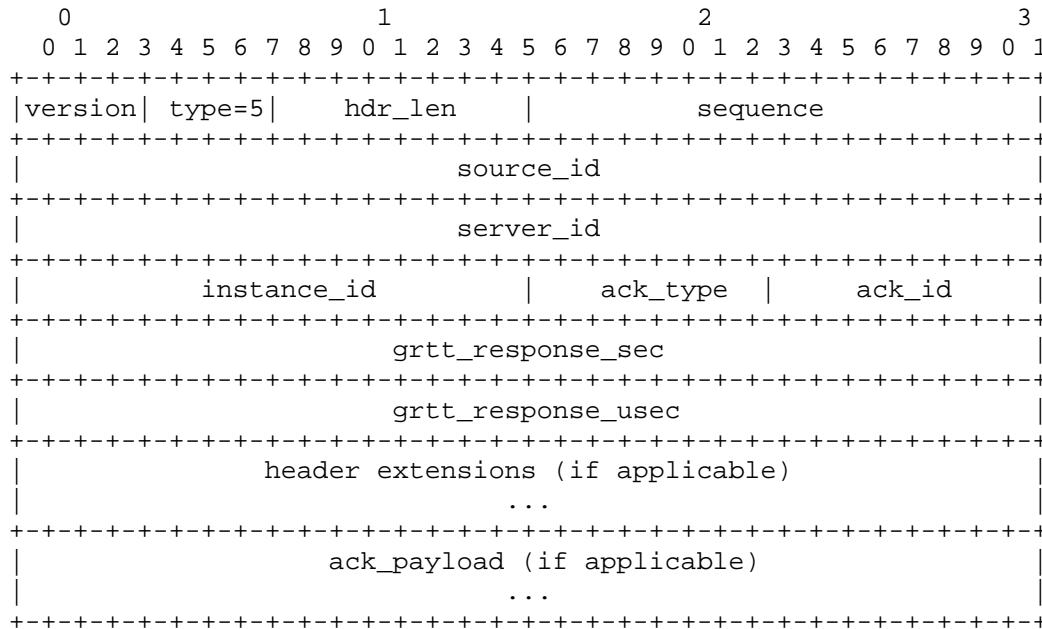
0          1          2          3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-----+-----+-----+-----+
|  form = 2   | flags = 0x01 |   length  = 24   |
+-----+-----+-----+-----+
| fec_id = 129 | reserved    | object_transport_id = 18 |
+-----+-----+-----+-----+
|                                     source_block_number = 6 |
+-----+-----+-----+-----+
| source_block_length = 32 | encoding_symbol_id = 5 |
+-----+-----+-----+-----+
| fec_id = 129 | reserved    | object_transport_id = 18 |
+-----+-----+-----+-----+
|                                     source_block_number = 6 |
+-----+-----+-----+-----+
| source_block_length = 32 | encoding_symbol_id = 10 |
+-----+-----+-----+-----+
|  form = 1   | flags = 0x05 |   length  = 12   |
+-----+-----+-----+-----+
| fec_id = 129 | reserved    | object_transport_id = 19 |
+-----+-----+-----+-----+
|                                     source_block_number = 1 |
+-----+-----+-----+-----+
| source_block_length = 32 | encoding_symbol_id = 3 |
+-----+-----+-----+-----+

```

4.3.2. NORM_ACK Message

The NORM_ACK message is intended to be used primarily as part of NORM congestion control operation and round-trip timing measurement. As mentioned in the NORM_CMD(ACK_REQ) message description, the acknowledgment type NORM_ACK_CC is provided for this purpose. The generation of NORM_ACK(CC) messages for round-trip timing estimation and congestion-control operation is described in Sections 5.5.1 and 5.5.2, respectively. However, some multicast applications may benefit from some limited form of positive acknowledgment for certain functions. A simple, scalable positive acknowledgment scheme is defined in Section 5.5.3 that can be leveraged by protocol implementations when appropriate. The NORM_CMD(FLUSH) may be used for OPTIONAL collection of positive acknowledgment of reliable reception to a certain "watermark" transmission point from specific receivers using this mechanism. The NORM_ACK type NORM_ACK_FLUSH is provided for this purpose and the format of the "nack_payload" for this acknowledgment type is given below. Beyond that, a range of

application-defined "ack_type" values is provided for use at the NORM application's discretion. Implementations making use of application-defined positive acknowledgments may also make use the "nack_payload" as needed, observing the constraint that the "nack_payload" field size be limited to a maximum of the NormSegmentSize for the sender to which the NORM_ACK is destined.



NORM_ACK Message Format

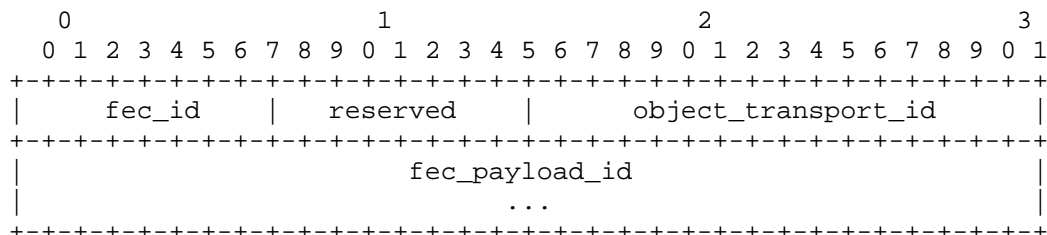
The NORM common message header fields serve their usual purposes.

The "server_id", "instance_id", and "grtt_response" fields serve the same purpose as the corresponding fields in NORM_NACK messages. And header extensions may be applied to support congestion control feedback or other functions in the same manner.

The "ack_type" field indicates the nature of the NORM_ACK message. This directly corresponds to the "ack_type" field of the NORM_CMD(ACK_REQ) message to which this acknowledgment applies.

The "ack_id" field serves as a sequence number so that the sender can verify that a NORM_ACK message received actually applies to a current acknowledgment request. The "ack_id" field is not used in the case of the NORM_ACK_CC and NORM_ACK_FLUSH acknowledgment types.

The "ack_payload" format is a function of the "ack_type". The NORM_ACK_CC message has no attached content. Only the NORM_ACK header applies. In the case of NORM_ACK_FLUSH, a specific "ack_payload" format is defined:



NORM_ACK_FLUSH "ack_payload" Format

The "object_transport_id" and "fec_payload_id" are used by the receiver to acknowledge applicable NORM_CMD(FLUSH) messages transmitted by the sender identified by the "server_id" field.

The "ack_payload" of NORM_ACK messages for application-defined "ack_type" values is specific to the application but is limited in size to a maximum the NormSegmentSize of the sender referenced by the "server_id".

4.4. General Purpose Messages

Some additional message formats are defined for general purpose in NORM multicast sessions whether the participant is acting as a sender and/or receiver within the group.

4.4.1. NORM_REPORT Message

This is an optional message generated by NORM participants. This message could be used for periodic performance reports from receivers in experimental NORM implementations. The format of this message is currently undefined. Experimental NORM implementations may define NORM_REPORT formats as needed for test purposes. These report messages SHOULD be disabled for interoperability testing between different NORM implementations.

5. Detailed Protocol Operation

This section describes the detailed interactions of senders and receivers participating in a NORM session. A simple synopsis of protocol operation is given here:

- 1) The sender periodically transmits NORM_CMD(CC) messages as needed to initialize and collect roundtrip timing and congestion control feedback from the receiver set.
- 2) The sender transmits an ordinal set of NormObjects segmented in the form of NORM_DATA messages labeled with NormTransportIds and logically identified with FEC encoding block numbers and symbol identifiers. NORM_INFO messages may optionally precede the transmission of data content for NORM transport objects.
- 3) As receivers detect missing content from the sender, they initiate repair requests with NORM_NACK messages. Note the receivers track the sender's most recent objectId::fecPayloadId transmit position and NACK_only_ for content ordinally prior to that transmit position. The receivers schedule random backoff timeouts before generating NORM_NACK messages and wait an appropriate amount of time before repeating the NORM_NACK if their repair request is not satisfied.
- 4) The sender aggregates repair requests from the receivers and logically "rewinds" its transmit position to send appropriate repair messages. The sender sends repairs for the earliest ordinal transmit position first and maintains this ordinal repair transmission sequence. Previously untransmitted FEC parity content for the applicable FEC coding block is used for repair transmissions to the greatest extent possible. If the sender exhausts its available FEC parity content on multiple repair cycles for the same coding block, it resorts to an explicit repair strategy (possibly using parity content) to complete repairs. (The use of explicit repair is expected to be an exception in general protocol operation, but the possibility does exist for extreme conditions). The sender immediately assumes transmission of new content once it has sent pending repairs.
- 5) The sender transmits NORM_CMD(FLUSH) messages when it reaches the end of enqueued transmit content and pending repairs. Receivers respond to the NORM_CMD(FLUSH) messages with NORM_NACK transmissions (following the same suppression backoff timeout strategy as for data) if they require further repair.
- 6) The sender transmissions are subject to rate control limits determined by congestion control mechanisms. In the baseline NORM-CC operation, each sender in a NormSession maintains its own independent congestion control state. Receivers provide congestion control feedback in NORM_NACK and NORM_ACK messages. NORM_ACK feedback for congestion control purposes is governed using a suppression mechanism similar to that for NORM_NACK messages.

While this overall concept is relatively simple, there are details to each of these aspects that need to be addressed for successful, efficient, robust, and scalable NORM protocol operation.

5.1. Sender Initialization and Transmission

Upon startup, the NORM sender immediately begins sending NORM_CMD(CC) messages to collect round trip timing and other information from the potential group. If NORM-CC congestion control operation is enabled, the NORM-CC Rate header extension **MUST** be included in these messages. Congestion control operation **SHALL** be observed at all times when operating in the general Internet. Even if congestion control operation is disabled at the sender, it may be desirable to use the NORM_CMD(CC) messaging to collect feedback from the group using the baseline NORM-CC feedback mechanisms. This proactive feedback collection can be used to establish a GRTT estimate prior to data transmission and potential NACK operation.

In some cases, applications may wish for the sender to also proceed with data transmission immediately. In other cases, the sender may wish to defer data transmission until it has received some feedback or request from the receiver set indicating that receivers are indeed present. Note, in some applications (e.g., web push), this indication may come out-of-band with respect to the multicast session via other means. As noted, the periodic transmission of NORM_CMD(CC) messages may precede actual data transmission in order to have an initial GRTT estimate.

With inclusion of the OPTIONAL NORM FEC Object Transmission Information Header Extension, the NORM protocol sender message headers can contain all information necessary to prepare receivers for subsequent reliable reception. This includes FEC coding parameters, the sender NormSegmentSize, and other information. If this header extension is not used, it is presumed that receivers have received the FEC Object Transmission Information via other means. Additionally, applications may leverage the use of NORM_INFO messages associated with the session data objects in the session to provide application-specific context information for the session and data being transmitted. These mechanisms allow for operation with minimal pre-coordination among the senders and receivers.

The NORM sender begins segmenting application-enqueued data into NORM_DATA segments and transmitting it to the group. The segmentation algorithm is described in Section 5.1.1. The rate of transmission is controlled via congestion control mechanisms or is a fixed rate if desired for closed network operations. The receivers participating in the multicast group provide feedback to the sender as needed. When the sender reaches the end of data it has enqueued

for transmission or any pending repairs, it transmits a series of NORM_CMD(FLUSH) messages at a rate of one per 2*GRTT. Receivers may respond to these NORM_CMD(FLUSH) messages with additional repair requests. A protocol parameter "NORM_ROBUST_FACTOR" determines the number of flush messages sent. If receivers request repair, the repair is provided and flushing occurs again at the end of repair transmission. The sender may attach an OPTIONAL "acking_node_list" to NORM_CMD(FLUSH) containing the NormNodeIds for receivers from which it expects explicit positive acknowledgment of reception. The NORM_CMD(FLUSH) message may be also used for this optional function any time prior to the end of data enqueued for transmission with the NORM_CMD(FLUSH) messages multiplexed with ongoing data transmissions. The OPTIONAL NORM positive acknowledgment procedure is described in Section 5.5.3.

5.1.1. Object Segmentation Algorithm

NORM senders and receivers must use a common algorithm for logically segmenting transport data into FEC encoding blocks and symbols so that appropriate NACKs can be constructed to request repair of missing data. NORM FEC coding blocks are comprised of multi-byte symbols which are transmitted in the payload of NORM_DATA messages. Each NORM_DATA message contains one source or encoding symbol and the NormSegmentSize sender parameter defines the maximum symbol size in bytes. The FEC encoding type and associated parameters govern the source block size (number of source symbols per coding block). NORM senders and receivers use these FEC parameters, along with the NormSegmentSize and transport object size to compute the source block structure for transport objects. These parameters are provided in the FEC Transmission Information for each object. The algorithm given below is used to compute a source block structure such that all source blocks are as close to being equal length as possible. This helps avoid the performance disadvantages of "short" FEC blocks. Note this algorithm applies only to the statically-sized NORM_OBJECT_DATA and NORM_OBJECT_FILE transport object types where the object size is fixed and predetermined. For NORM_OBJECT_STREAM objects, the object is segmented according to the maximum source block length given in the FEC Transmission Information, unless the FEC Payload ID indicates an alternative size for a given block.

The NORM block segmentation algorithm is defined as follows. For a transport object of a given length (L_{obj}) in bytes, a first number of FEC source blocks (N_{large}) is delineated of a larger block size (B_{large}), and a second number of source blocks (N_{small}) is delineated of a smaller block size (B_{small}). Given the maximum FEC source block size (B_{max}) and the sender's NormSegmentSize, the block segmentation for a given NORM transport object is determined as follows:

Inputs:

B_max = Maximum source block length (i.e., maximum number of source symbols per source block)

L_sym = Encoding symbol length in bytes (i.e., NormSegmentSize)

L_obj = Object length in bytes

Outputs:

N_total = The total number of source blocks into which the transport object is partitioned.

N_large = Number of larger source blocks (first set of blocks)

B_large = Size (in encoding symbols) of the larger source blocks

N_small = Number of smaller source blocks (second set of blocks)

B_small = Size (in encoding symbols) of the smaller source blocks

L_final = Length (in bytes) of the last source symbol of the last source block (All other symbols are of length L_sym).

Algorithm:

- 1) The total number of source symbols in the transport object is computed as: $S_{total} = L_{obj}/L_{sym}$ [rounded up to the nearest integer]
- 2) The transport object is partitioned into N_total source blocks, where: $N_{total} = S_{total}/B_{max}$ [rounded up to the nearest integer]
- 3) The average length of a source block is computed as: $B_{ave} = S_{total}/N_{total}$ (this may be non-integer)
- 4) The size of the first set of larger blocks is computed as:
 $B_{large} = B_{ave}$ [rounded up to the nearest integer] (Note it will always be the case that $B_{large} \leq B_{max}$)
- 5) The size of the second set of smaller blocks is computed as:
 $B_{small} = B_{ave}$ [rounded down to the nearest integer] (Note if B_{ave} is an integer $B_{small} = B_{large}$; otherwise $B_{small} = B_{large} - 1$)

- 6) The fractional part of B_{ave} is computed as: $B_{fraction} = B_{ave} - B_{small}$
- 7) The number of larger source blocks is computed as: $N_{large} = B_{fraction} * N_{total}$ (Note N_{large} is an integer in the range 0 through $N_{total} - 1$)
- 8) The number of smaller source blocks is computed as: $N_{small} = N_{total} - N_{large}$
- 9) Each of the first N_{large} source blocks consists of B_{large} source symbols. Each of the remaining N_{small} source blocks consists of B_{small} source symbols. All symbols are L_{sym} bytes in length except for the final source symbol of the final source block which is of length (in bytes):
$$L_{final} = L_{obj} - (N_{large} * B_{large} + N_{small} * B_{small} - 1) * L_{sym}$$

5.2. Receiver Initialization and Reception

The NORM protocol is designed such that receivers may join and leave the group at will. However, some applications may be constrained such that receivers need to be members of the group prior to start of data transmission. NORM applications may use different policies to constrain the impact of new receivers joining the group in the middle of a session. For example, a useful implementation policy is for new receivers joining the group to limit or avoid repair requests for transport objects already in progress. The NORM sender implementation may wish to impose additional constraints to limit the ability of receivers to disrupt reliable multicast performance by joining, leaving, and rejoining the group often. Different receiver "join policies" may be appropriate for different applications and/or scenarios. For general purpose operation, default policy where receivers are allowed to request repair only for coding blocks with a NormTransportId and FEC coding block number greater than or equal to the first non-repair NORM_DATA or NORM_INFO message received upon joining the group is RECOMMENDED. For objects of type NORM_OBJECT_STREAM it is RECOMMENDED that the join policy constrain receivers to start reliable reception at the current FEC coding block for which non-repair content is received.

5.3. Receiver NACK Procedure

When the receiver detects it is missing data from a sender's NORM transmissions, it initiates its NACKing procedure. The NACKing procedure SHALL be initiated only at FEC coding block boundaries, NormObject boundaries, and upon receipt of a NORM_CMD(FLUSH) message.

The NACKing procedure begins with a random backoff timeout. The duration of the backoff timeout is chosen using the "RandomBackoff" algorithm described in the NORM Building Block document [4] using $(K_{sender} * GRTT_{sender})$ for the "maxTime" parameter and the sender advertised group size (G_{SIZE}_{sender}) as the "groupSize" parameter. NORM senders provide values for $GRTT_{sender}$, K_{sender} and G_{SIZE}_{sender} via the "grtt", "backoff", and "gsize" fields of transmitted messages. The $GRTT_{sender}$ value is determined by the sender based on feedback it has received from the group while the K_{sender} and G_{SIZE}_{sender} values may be determined by application requirements and expectations or ancillary information. The backoff factor " K_{sender} " MUST be greater than one to provide for effective feedback suppression. A value of $K = 4$ is RECOMMENDED for the Any Source Multicast (ASM) model while a value of $K = 6$ is RECOMMENDED for Single Source Multicast (SSM) operation.

Thus:

$$T_{backoff} = \text{RandomBackoff}(K_{sender} * GRTT_{sender}, G_{SIZE}_{sender})$$

To avoid the possibility of NACK implosion in the case of sender or network failure during SSM operation, the receiver SHALL automatically suppress its NACK and immediately enter the "holdoff" period described below when $T_{backoff}$ is greater than $(K_{sender} - 1) * GRTT_{sender}$. Otherwise, the backoff period is entered and the receiver MUST accumulate external pending repair state from NORM_NACK messages and NORM_CMD(REPAIR_ADV) messages received. At the end of the backoff time, the receiver SHALL generate a NORM_NACK message only if the following conditions are met:

- 1) The sender's current transmit position (in terms of `objectId::fecPayloadId`) exceeds the earliest repair position of the receiver.
- 2) The repair state accumulated from NORM_NACK and NORM_CMD(REPAIR_ADV) messages do not equal or supersede the receiver's repair needs up to the sender transmission position at the time the NACK procedure (backoff timeout) was initiated.

If these conditions are met, the receiver immediately generates a NORM_NACK message when the backoff timeout expires. Otherwise, the receiver's NACK is considered to be "suppressed" and the message is not sent. At this time, the receiver begins a "holdoff" period during which it constrains itself to not reinitiate the NACKing process. The purpose of this timeout is to allow the sender worst-case time to respond to the repair needs before the receiver requests repair again. The value of this "holdoff" timeout ($T_{rcvrHoldoff}$) as described in [4] is:

$$T_rcvrHoldoff = (Ksender + 2) * GRTTsender$$

The NORM_NACK message contains repair request content beginning with lowest ordinal repair position of the receiver up through the coding block prior to the most recently heard ordinal transmission position for the sender. If the size of the NORM_NACK content exceeds the sender's NormSegmentSize, the NACK content is truncated so that the receiver only generates a single NORM_NACK message per NACK cycle for a given sender. In summary, a single NACK message is generated containing the receiver's lowest ordinal repair needs.

For each partially-received FEC coding block requiring repair, the receiver SHALL, on its `_first_` repair attempt for the block, request the parity portion of the FEC coding block beginning with the lowest ordinal `_parity_` "encoding_symbol_id" (i.e., "encoding_symbol_id" = "source_block_len") and request the number of FEC symbols corresponding to its data segment erasure count for the block. On `_subsequent_` repair cycles for the same coding block, the receiver SHALL request only those repair symbols from the first set it has not yet received up to the remaining erasure count for that applicable coding block. Note that the sender may have provided other different, additional parity segments for other receivers that could also be used to satisfy the local receiver's erasure-filling needs. In the case where the erasure count for a partially-received FEC coding block exceeds the maximum number of parity symbols available from the sender for the block (as indicated by the NORM_DATA "fec_num_parity" field), the receiver SHALL request all available parity segments plus the ordinally highest missing data segments required to satisfy its total erasure needs for the block. The goal of this strategy is for the overall receiver set to request a lowest common denominator set of repair symbols for a given FEC coding block. This allows the sender to construct the most efficient repair transmission segment set and enables effective NACK suppression among the receivers even with uncorrelated packet loss. This approach also requires no synchronization among the receiver set in their repair requests for the sender.

For FEC coding blocks or NormObjects missed in their entirety, the NORM receiver constructs repair requests with NORM_NACK_BLOCK or NORM_NACK_OBJECT flags set as appropriate. The request for retransmission of NORM_INFO is accomplished by setting the NORM_NACK_INFO flag in a corresponding repair request.

5.4. Sender NACK Processing and Response

The principle goal of the sender is to make forward progress in the transmission of data its application has enqueued. However, the sender must occasionally "rewind" its logical transmission point to

satisfy the repair needs of receivers who have NACKed. Aggregation of multiple NACKs is used to determine an optimal repair strategy when a NACK event occurs. Since receivers initiate the NACK process on coding block or object boundaries, there is some loose degree of synchronization of the repair process even when receivers experience uncorrelated data loss.

5.4.1. Sender Repair State Aggregation

When a sender is in its normal state of transmitting new data and receives a NACK, it begins a procedure to accumulate NACK repair state from NORM_NACK messages before beginning repair transmissions. Note that this period of aggregating repair state does not interfere with its ongoing transmission of new data.

As described in [4], the period of time during which the sender aggregates NORM_NACK messages is equal to:

$$T_sndrAggregate = (Ksender+1)*GRTT$$

where "Ksender" is the same backoff scaling value used by the receivers, and "GRTT" is the sender's current estimate of the group's greatest round-trip time.

When this period ends, the sender "rewinds" by incorporating the accumulated repair state into its pending transmission state and begins transmitting repair messages. After pending repair transmissions are completed, the sender continues with new transmissions of any enqueued data. Also, at this point in time, the sender begins a "holdoff" timeout during which time the sender constrains itself from initiating a new repair aggregation cycle, even if NORM_NACK messages arrive. As described in [4], the value of this sender "holdoff" period is:

$$T_sndrHoldoff = (1*GRTT)$$

If additional NORM_NACK messages are received during this sender "holdoff" period, the sender will immediately incorporate these "late messages" into its pending transmission state ONLY if the NACK content is ordinally greater than the sender's current transmission position. This "holdoff" time allows worst case time for the sender to propagate its current transmission sequence position to the group, thus avoiding redundant repair transmissions. After the holdoff timeout expires, a new NACK accumulation period can be begun (upon arrival of a NACK) in concert with the pending repair and new data transmission. Recall that receivers are not to initiate the NACK repair process until the sender's logical transmission position exceeds the lowest ordinal position of their repair needs. With the

new NACK aggregation period, the sender repeats the same process of incorporating accumulated repair state into its transmission plan and subsequently "rewinding" to transmit the lowest ordinal repair data when the aggregation period expires. Again, this is conducted in concert with ongoing new data and/or pending repair transmissions.

5.4.2. Sender FEC Repair Transmission Strategy

The NORM sender should leverage transmission of FEC parity content for repair to the greatest extent possible. Recall that the receivers use a strategy to request a lowest common denominator of explicit repair (including parity content) in the formation of their NORM_NACK messages. Before falling back to explicitly satisfying different receivers' repair needs, the sender can make use of the general erasure-filling capability of FEC-generated parity segments. The sender can determine the maximum erasure filling needs for individual FEC coding blocks from the NORM_NACK messages received during the repair aggregation period. Then, if the sender has a sufficient number (less than or equal to the maximum erasure count) of previously unsent parity segments available for the applicable coding blocks, the sender can transmit these in lieu of the specific packets the receiver set has requested. Only after exhausting its supply of "fresh" (unsent) parity segments for a given coding block should the sender resort to explicit transmission of the receiver set's repair needs. In general, if a sufficiently powerful FEC code is used, the need for explicit repair will be an exception, and the fulfillment of reliable multicast can be accomplished quite efficiently. However, the ability to resort to explicit repair allows the protocol to be reliable under even very extreme circumstances.

NORM_DATA messages sent as repair transmissi